ISWA
International Solid Waste Association

BENEFITS OF COMPOST AND ANAEROBIC DIGESTATE WHEN APPLIED TO SOIL

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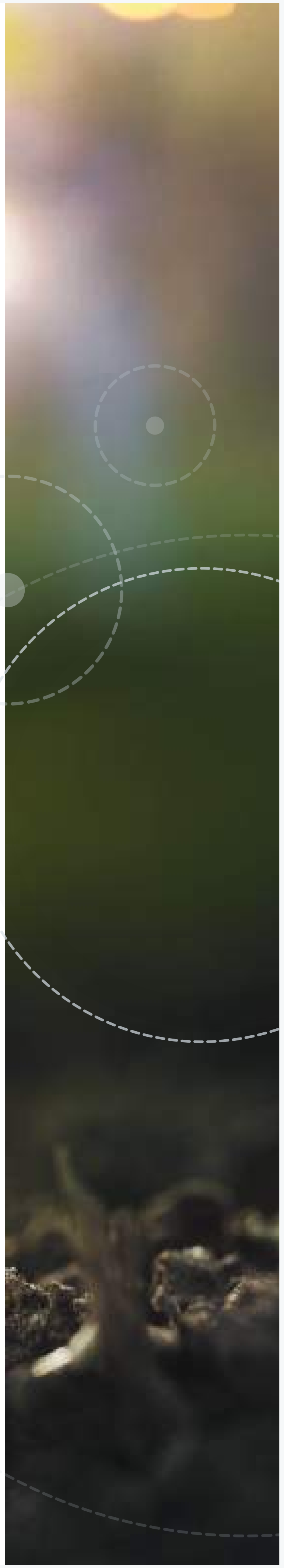

1

Executive summary

Soil is a complex mixture of minerals, organic matter, air and water. It can take many thousands of years to form but can be destroyed very quickly (sometimes within decades) through poor land management practices, urban development and the effects of climate change. It covers most of the earth's surface and supports almost all terrestrial life. However, soil is under threat: it is thought that about a third is moderately to highly degraded due, *inter alia,* to erosion, nutrient depletion and pollution. Over the last 40 years about 30% of the world's cropland has become unproductive, with an estimated 10 million hectares of agricultural land being lost through soil erosion every year.

It is estimated that just under a billion tonnes of municipal organic solid waste is generated globally every year, although about a third of it is not managed in an 'environmentally safe manner', leading to the creation of odours, release of the powerful greenhouse gas methane into the atmosphere and attraction of vermin. The vast majority of this organic waste is derived from soil, either directly as plants (such as arable and horticultural crops, plant-based food waste and garden/landscaping/forestry residues) or indirectly as animal products (such as meat, milk, manures and abattoir wastes). As this organic waste is a valuable resource, containing both carbon and plant nutrients, recycling it through composting and anaerobic digestion helps return these valuable resources to the soil from which they were originally derived.

Organic wastes are composed of a variety of organic compounds, of which cellulose is the main chemical constituent, followed by lignin and hemicellulose. A diverse range of micro-organisms are responsible for biodegrading organic wastes, with bacteria dominating in anaerobic digestion systems, and both bacteria and fungi being fundamental to the composting process. Lignin, which is the structural component in wood, is present in organic wastes derived from parks and gardens. It is only degraded in aerobic (oxygen containing) environments through the action of some fungi and certain types of bacteria called actinomycetes.

The composting process involves a biochemical process called 'humification' which results in the formation of stable organic matter (humic substances). However, there is little scientific evidence of humification occurring during anaerobic digestion, which reflects both the process and the properties of digested wastes.

Experiments have shown that greater amounts of carbon remain in the soil when organic wastes are composted, rather than applied directly. In addition, the organic matter in compost is thought to be further transformed through soil microbes into more stable forms of carbon in soil.

Compost can be classified as an organic soil improver

As it contributes positively towards soil's organic matter content but has low nutrient levels relative to anaerobic digestate. This helps improve soil structure, reduces erosion, helps maintain soil tilth and acts as a 'nutrient bank'. Applying compost to soil has been shown to increase soil microbial biomass and microbial activity, and build up a pool of plant nutrients. It is also an important reservoir of carbon, storing more than the atmosphere and terrestrial vegetation combined.

Compost has the potential to sequester carbon in soil:

- Studies have shown that over a period of 4-12 years between **11% - 45%** of the organic carbon applied to soil as compost remained as **soil organic carbon.**

- **Soil organic carbon** increases of between **50-70 kg** C ha^{-1} yr^{-1} t^{-1} dry solids applied as compost are possible.

- **Every tonne** of soil organic carbon holds the equivalent of about **3.67** tonnes of atmospheric carbon dioxide.

- **One tonne** (fresh mass) of green waste derived-compost applied to soil over one hectare (10,000 square meters) results in a net CO_2-eq saving of **143 kg** ha^{-1} $year^{-1}$ due to the increase in soil organic matter alone.

The main benefits to soils following compost application are thought to be realised in the first 20 years until a new organic matter equilibrium is reached.

Repeated compost application has been shown to increase soil aggregate stability and soil pore structure, reduce compaction and increase water holding capacity.

Digestate can be classified as an organic fertiliser

As its main function is to supply plant nutrients. Studies have shown increased crop yields following digestate application due to its high nutrient content; as these are present in mineral form, they are readily available for crop uptake. However, compared to compost, there is little evidence of humification during the anaerobic digestion process and lignin-containing materials are generally not treated anaerobically. The long-term benefits to soil of anaerobic digestate are less clear cut than those of compost, and it is thought that it has a negligible effect on soil organic matter in the long term.

The reader should be aware that this report focuses on organic matter in soil and thus the value of biogas produced during anaerobic digestion has not been considered in this document; however, when making a more general comparison between composting and anaerobic digestion of organic waste, the significant role of biogas, a renewable and carbon neutral fuel, should be taken into consideration by waste planners and decision makers.

Focusing on the benefits of recycling organic waste and returning it back to soils, in most parts of the world, composting and anaerobic digestion are mainly carried out as mutually exclusive processes. The generation of biomethane during AD provides a valuable non-fossil fuel energy source and an organic fertiliser; however, benefits to soil can be further enhanced through effective aerobic post stabilisation to transform any residual carbon in digestate into more stable forms.

The implications for increasing soil organic matter content are therefore potentially significant.

The next report in this series will provide estimates of the potential theoretical benefits to soil that can be achieved globally and in a number of different countries, each having different soil types and climatic conditions.

2

Introduction

The Importance of Quality Compost & Digestate

This report sets out the benefits to soil of applying compost and anaerobic digestate derived from organic solid wastes, with the information having been derived from peer reviewed scientific papers or governmental reports.

It is important to note that the benefits described in this report may only be realised if the compost/digestate is of high quality; meaning it is not contaminated. Physical and chemical contaminants, such as plastics, glass, metals, heavy metals and organic substances, might pollute soil and have the potential to accumulate over time following repeated application of contaminated compost/digestate. This is not sustainable, and neither is it desirable.

Quality compost and digestate should only be derived from clean organic (bio-waste) feedstocks which have been kept and collected separately from other wastes. In addition, it is also important to ensure that composting or anaerobic digestion processes are quality assured, with the end products being tested regularly to monitor quality. Quality standards exist in many parts of the world, so readers should consult those that are most relevant to their local situation.

Due to the different characteristics and potential contamination levels in mixed waste derived compost/digestate, sewage sludge and biochar, these materials have been excluded from the scope of this document.

The Link Between Organic Wastes & Soil

- Organic waste production (urban MSW generation) amounts to an estimated **935 million** tonnes / year.
- About **0.35 kg** per capita of organic waste is produced every day.
- About **33%** of the world's municipal solid waste is not managed in an 'environmentally safe manner', leading to odours, vermin and methane generation.
- Approximately **80%** of the world's agricultural land suffers moderate to severe erosion.
- An estimated **10 million** ha of agricultural land are lost through soil erosion every year (~0.7% of the total).
- Over the last 40 years about **30%** of world's cropland has become unproductive.
- **Recycling organic matter** can help address these problems.
- It addresses the **United Nations Sustainable Development Goals** 12 & 15.

United Nations Sustainable Development Goals

The 2030 Agenda for Sustainable Development was adopted by all United Nations Member States in 2015 and sets out a framework for peace and prosperity for people and the planet.

There are a total of 17 Sustainable Development Goals (SDGs), each of which has a number of specific targets (169 in total), providing a framework for action.

The targets most relevant to this report include:

Goal 12 - Ensure sustainable consumption and production patterns

- 12.2 - **by 2030**, achieve the sustainable management and efficient use of natural resources
- 12.4 - **by 2020**, achieve the environmentally sound management of chemicals and all wastes
- 12.5 - **by 2030**, substantially reduce waste generation through prevention, reduction, recycling and reuse

Goal 15 - Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss

- 15.3 - by 2030, combat desertification, restore degraded land and soil

https://sustainabledevelopment.un.org/

> Globally, organic wastes form a significant fraction of the solid waste stream, with estimates of between 44-46% (by mass) of the municipal solid waste (MSW) fraction. It is thought that just under **one billion tonnes of organic waste is produced annually,** equivalent to 0.35 kg / capita / day (ISWA, in press). With increasing urbanisation and a growing global population, this means that organic wastes arisings will not only continue to grow but will also become increasingly concentrated in cities.

The World Bank has estimated, that in 2016, at least 33% of the world's municipal solid waste was not managed in an 'environmentally safe manner' *(Kaza et al. 2018).* As the majority of the organic waste fraction is highly putrescible, it can rapidly decompose, creating odours, attracting vermin and emitting methane (a powerful greenhouse gas). This presents a significant challenge for waste planners, waste managers, urban administrators and citizens, as its efficient collection and effective treatment is a key public health service that also has global implications in terms of climate change.

The vast majority of organic waste is derived from soil, either directly as plants (such as arable and horticultural crops, and garden/landscaping/forestry residues) or indirectly as animal products (such as meat, milk, manures and abattoir wastes). This means that soil is the main source of most organic wastes generated[1].

However, there is growing recognition that the quality of soil across the world is diminishing. It has been estimated that 80% of the world's agricultural land suffers moderate to severe erosion, with 10 million hectares (ha) of agricultural land being lost through soil erosion every year. Worryingly, over the last 40 years, about 30% of the world's cropland has become unproductive, with the loss of soil organic matter cited as a major contributor (Pimentell & Burgess 2013).

The link between recycling societies' organic wastes (through composting and anaerobic digestion) and the soil from which these wastes have been generated is not as clear cut as it should be. Farmers and agronomists have known about the benefits of applying a variety of organic wastes to agricultural soil for millennia; however, these benefits are often only communicated in terms of increases in crop yields due to their fertiliser content. Their effects on a soil's organic matter content is often overlooked, or left to the realm of soil scientists, where many detailed reports exist; it is a subject that is seldom considered when developing strategies for solid waste management and recycling, although it is now being considered in the European Union as part of reforms to the Common Agricultural Policy (European Commission 2019).

The aim of this report is therefore to help fill the information gap about the benefits of organic matter in compost and digestate when applied to soils, and directly addresses some of the Sustainable Development Goals set by the United Nations (see box). It is aimed at ISWA members, waste planners and managers, policy officers and other stakeholders with an interest in the link between sustainable waste management and sustainable land and agricultural practices.

This report distils the findings of numerous peer-reviewed scientific papers. It summarises some of the important issues in a format that can be read and understood by professionals from a wide range of sectors and educational backgrounds.

In line with the terms of reference of the project agreed by ISWA, the focus has been on organic solid wastes, but excludes sewage sludge and biochar. In addition, this report does not constitute a life-cycle assessment or greenhouse gas inventory analysis.

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[1] Marine and other aquatic environments make up the rest.

3

Understanding soil

Soil

- Soil is a complex mixture of minerals, organic matter, air and water.
- Soil varies considerably and can take many thousands of years to form; but can be destroyed very quickly (within decades) through poor land management practices, urban development and the effects of climate change.
- Soil covers most of the earth's surface and supports almost all terrestrial life; it is the main receptor of compost and digestate.
- 33 percent of soil is moderately to highly degraded due to erosion, nutrient depletion, acidification, salinization, compaction and chemical pollution.
- Soil organic matter helps provide soil structure, reduces erosion, improves water retention, helps maintain soil tilth and acts as a 'nutrient bank'.
- Soil organic matter is an important reservoir of carbon, storing more than the atmosphere and terrestrial vegetation combined.

As soil is the main receptor for compost and digestate, it is important to understand what it is and how it is influenced by organic matter additions. This chapter provides a brief overview of the composition of soil, its role and function, and the effects of applying organic matter.

Definition of soil

Soil is a complex mixture of minerals, organic matter, air and water. The minerals are largely derived from the underlying rocks, the organic matter from plants, animals and microbes living on or in the upper layers, and the water from both precipitation and underground sources.

Soil is a function of the combined effects of climate, topography, animals and plants, and the ways in which these interact with the underlying geology.

Topsoil is the upper, outermost layer of soil. It has the highest concentration of organic matter and micro-organisms and is where most of the Earth's biological soil activity occurs.

Globally, soil varies considerably and can take many thousands of years to form. However, it can also be destroyed very quickly through poor land management practices, urban development and the effects of climate change.

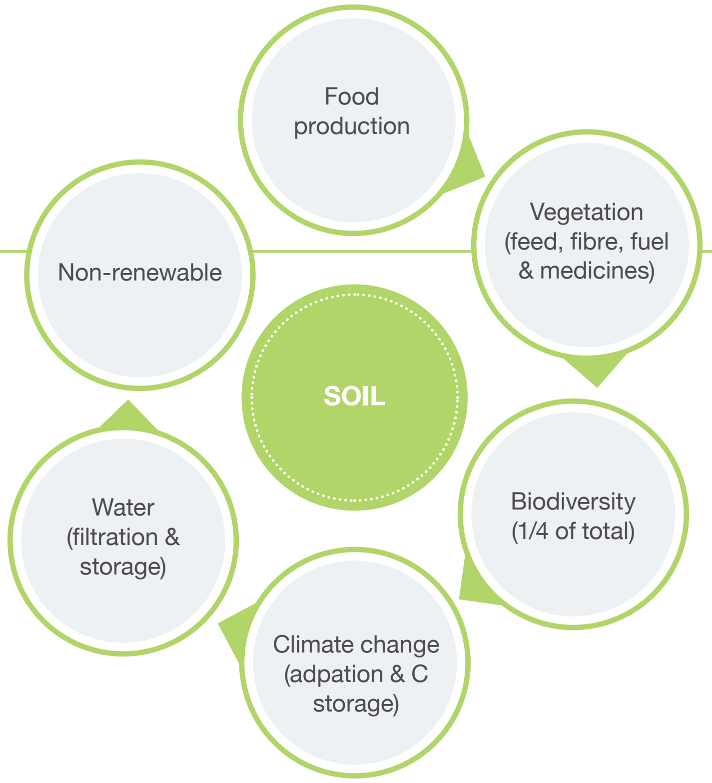
Soil average composition

3.1

Figure 1 – The role of soil

Soil covers most of the earth's surface and supports almost all terrestrial life.

It is a non-renewable resource and supplies a range of ecosystem services, as well as providing humans with a medium on which to grow food (Figure 1). Due to the inherent complexity of these services, economic estimates are difficult to make.



3.2

Threats to soil

Although soils can take many thousands of years to form, they can also be destroyed very quickly. The 'Dust Bowl' of 1930s America illustrates how poor land management practices led to catastrophic topsoil losses within a decade, resulting in devastating social, environmental and economic impacts (see box).

Today the Food and Agriculture Organization of the United Nations (FAO 2015a) has estimated that '33 percent of soil is moderately to highly degraded due to erosion, nutrient depletion, acidification, salinization, compaction and chemical pollution'. This estimate contrasts with that of Pimentel & Burgess (2013) who suggested that approximately 80% of the world's agricultural land (which is about 50% of the total land area) suffers moderate to severe erosion. The authors also note that: 'soil is being lost from agricultural areas 10 to 40 times faster than the rate of soil formation imperilling humanity's food security'.

The 1930s Dust Bowl

The Dust Bowl affected parts of the USA and Canada during the 1930s and was the result of deep ploughing of native prairie grasslands during the previous decade. These farming practices resulted in the loss of surface grasses that had helped bind the soil and lock-in moisture. When a series of droughts hit the area during the 1930s, the topsoil was blown away in the wind, creating the iconic 'dust bowl' as immortalised by John Steinbeck in the Grapes of Wrath It is estimated that the Dust Bowl cost in the region of USD 450 billion per day (in 2018 terms), left over half a million people homeless, and resulted in the loss of over 770 million tonnes of topsoil from the southern plains in 1935 alone. Overall, every hectare of agricultural land is thought to have lost about 1,000 tonnes of topsoil.

https://en.wikipedia.org/wiki/Dust_Bowl

http://kinsleylibrary.info/wp-content/uploads/2014/10/Handi-facts.pdf

It is thought that loss of soil organic matter represents a significant threat to agricultural productivity. Soil organic matter losses are particularly acute in certain parts of the world, especially those that have been farmed intensively. Ploughing of soil over decades in temperate regions has also resulted in a steady decline of soil organic matter levels *(Schils et al. 2008).* 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.

3.3

Why soil organic matter matters

The organic fraction of soil is derived from both plant and animal material that has been returned to the soil and is in various stages of decomposition. It is sometimes referred to as soil organic matter (SOM), and sometimes as soil organic carbon (SOC); the difference between the two definitions is shown in the box.

Definitions

Soil Carbon

This is the total amount of carbon in a soil, and includes both organic carbon (derived from plants and animals) as well as inorganic carbon (usually present as carbonates and bicarbonates).

Soil Organic Carbon (SOC)

This is the carbon present in organic forms, and is derived from living things such as plants, animals and microbes.

Soil Organic Matter (SOM)

This is the soil organic carbon plus the hydrogen, oxygen and nitrogen that are part of the organic compounds. Scientists usually use the following equation to convert SOC to SOM:

SOIL ORGANIC MATTER (%) = SOIL ORGANIC CARBON (%) x 1.72

Carbon Management Index

This is a means of measuring soil carbon and how labile the carbon is, and can be used to monitor changes in soil carbon pools over time and whether interventions are increasing or decreasing SOM (Sodhi *et al.* 2009).

Figure 2 – The functions of soil organic matter

Globally, it is thought that soil organic matter is an important reservoir of carbon. Recent estimates by the FAO and ITPS (2018), suggest that the Global Soil Organic Carbon Stock for topsoil (in the top 0 to 30 cm) is 680 billion tonnes. It is thought that the total amount of carbon in soil is greater than that stored in both the atmosphere and terrestrial vegetation combined.

Soil organic carbon levels vary considerably between climatic zones and the type of land cover. Overall, tropical areas are thought to hold the most soil organic carbon (Table 1).

In terms of land cover, forested areas hold the greatest SOC (Table 2).

Figure 3 shows how SOC is distributed globally.

Please note that the estimated quantities shown in Tables 2 and 3 do not sum to 680 billion tonnes due to differences in methodologies used in the different climatic zones and land cover classes.

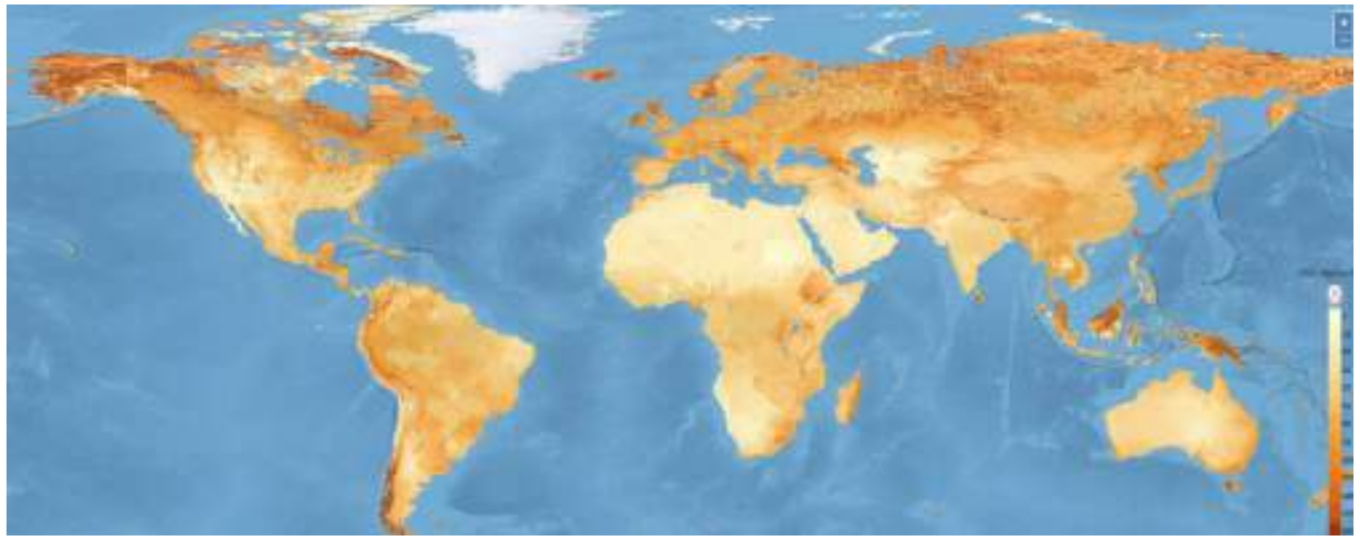
Table 1 – Global carbon stocks per climate zone

CLIMATE ZONE	QUANTITY OF SOC (billion tonnes)	PERCENTAGE OF TOTAL
Tropics	208	31%
Temperate	191	29%
Boreal	140	21%
Subtropics	102	15%
Arctic	20	3%

Table 2 – Global carbon stocks per land cover class

LAND COVER CLASS	QUANTITY OF SOC (billion tonnes)	PERCENTAGE OF TOTAL
Forests	216	33%
Savannas & shrublands	197	30%
Croplands & grasslands	155	24%
Mosaic of natural vegetation, croplands & grasslands	39	6%
Barren or sparsely vegetated lands	33	5%
Permanent wetlands	11	2%

Figure 3 – Global soil organic carbon map (Source: FAO & ITPS 2018)



Erosion of soils can lead to degradation of soil organic carbon, which can be released as carbon dioxide or methane; both of which are greenhouse gasses. Soil erosion therefore can contribute to climate change; whilst conversely, increasing soil organic matter can help sequester carbon. This is discussed again in more detail in Chapter 5.

Soil organic matter (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’.

Humus is made up of a complex mixture of humic acids, fulvic acids and humins (see Section 4.2; Box ‘Humification & Humic Substances’).

The turnover rate of SOM can vary considerably, from years, decades, to millennia. It is thought that the rate of SOM turnover (which influences how long it will remain in the soil) is not only influenced by its chemical composition, but also by the extent to which it binds to minerals, especially clays. This is thought to ‘protect’ the SOM from degradation and is discussed further in Section 5. Stable SOM is now thought to be the product of microbial activity in the soil (FAO 2015b).

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 of carbon dioxide (CO_2) per annum (Van-Camp *et al.* 2004). Despite there being a huge uncertainty surrounding this estimate, it illustrates the significant carbon sequestration potential of stable organic matter and its potential to mitigate greenhouse gas emissions.

Changes to land use and land cover change (LULCC) are also important factors in affecting the dynamics of soil organic matter formation and decomposition (Victoria *et al.* 2012). In particular, agriculture has been shown to reduce SOM, primarily due to ploughing and tillage practices. Scharlemann *et al.* (2014) 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, including the addition of organic matter amendments, such as compost. The next section discusses this in greater detail.

Overall, there is good evidence to suggest that the application of organic materials to soil increases its organic matter content. Long term (160 year) field experiments at Rothamsted in England showed significant increases in SOM content following annual applications of farmyard manures, especially in the early years (Powlson *et al.* 2011; Rothamsted 2018).

The benefits of adding organic materials, including compost, to soil are numerous and depends upon a complex interplay between soil type, the type of organic matter, the climate and the way in which the land is used. The main benefits have been summarised in Figure 4 and in the text box.

Benefits of applying organic matter to soil

Regularly applying quality organic materials to soil can result in the following physical, chemical and biological benefits:

- **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 fertiliser 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.

- **Increasing soil pH (liming effect)**

  Composts can reduce the acidity of soils, which helps release micronutrients, making them available for plant uptake.

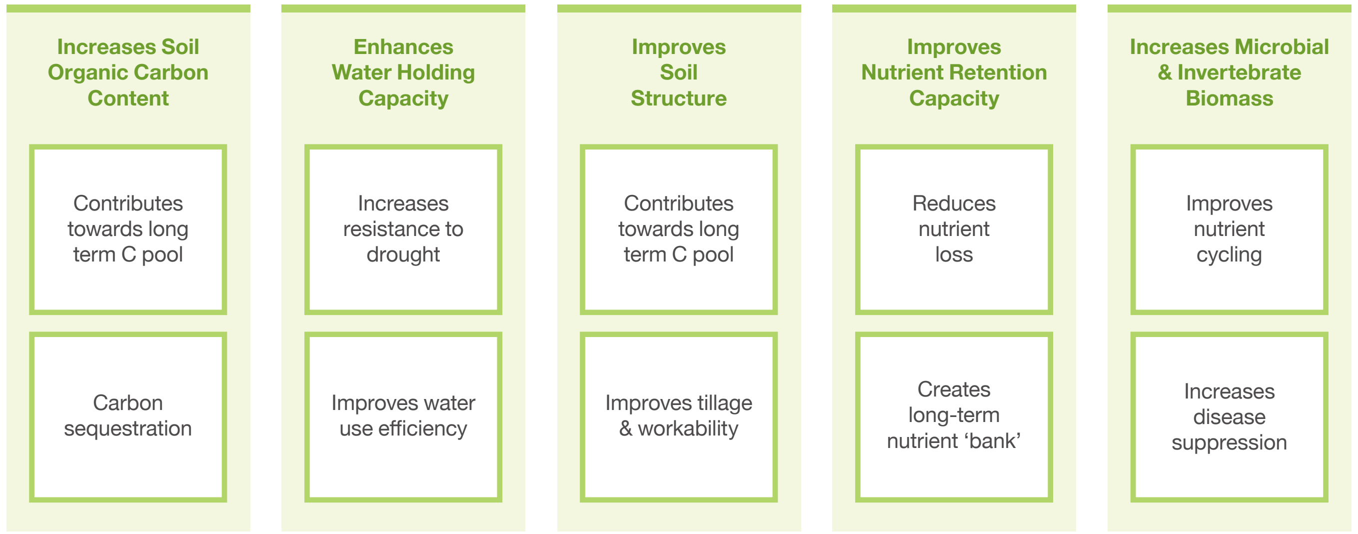


Figure 4 – The benefits of adding organic amendments to soil (Adapted from Diacono & Montemurro, 2010)

Figure 5 – Simplified schematic flow of organic matter in soil used in the CQESTR model

Following application of organic matter to soil, it is thought that the organic compounds decompose at different rates. The CQESTR soil model, developed in the USA, assumes that there are broadly three phases of decomposition:

Phase I

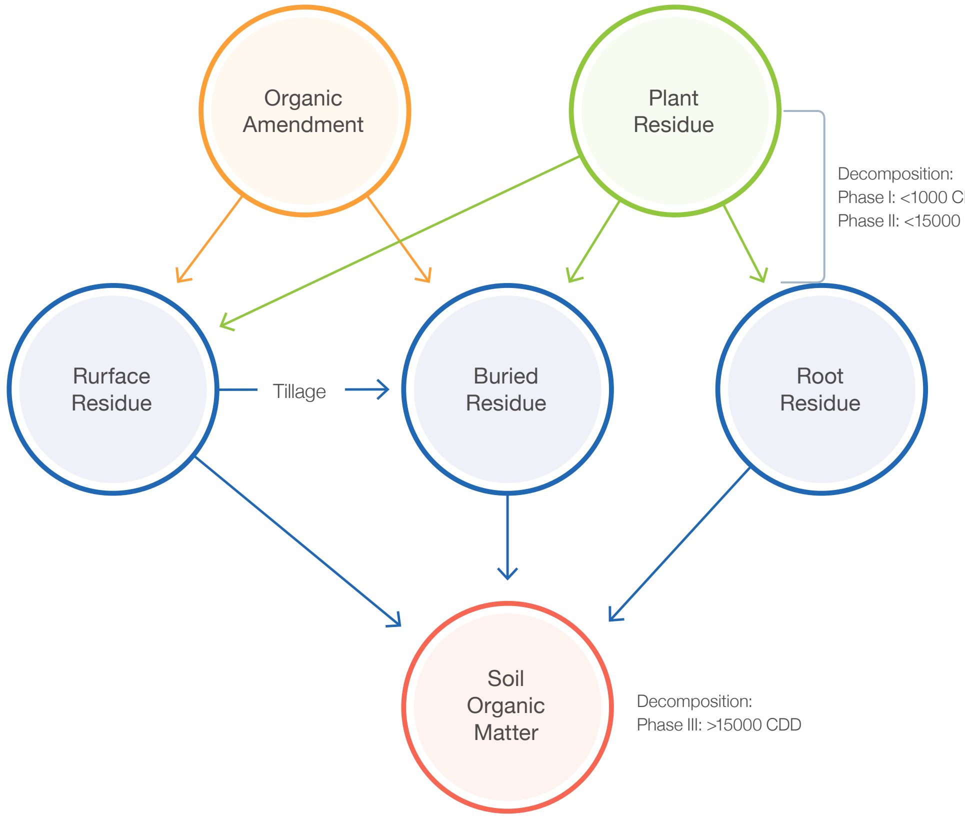
Rapid decomposition (occurs in the short term; less than 1,000 CDD[2]);

Phase II

Slow decomposition, where the more stable compounds are degraded (occurs in the medium term; less than 15,000 CDD); and

Phase III

Transfer of organic matter to the stable soil organic matter pool (long term; over 15,000 CDD).



The CQESTR model

This is a model developed by the United States Department of Agriculture - Agricultural Research Service (USDA-ARS). It calculates biological decomposition rates of crop residue or organic amendments as they are converted to soil organic matter or soil organic carbon.

It can be used to assess the effect of agricultural management practices, including compost addition, on short- and long-term SOM dynamics.

https://www.ars.usda.gov/pacific-west-area/pendleton/swcr/docs/cqestr/

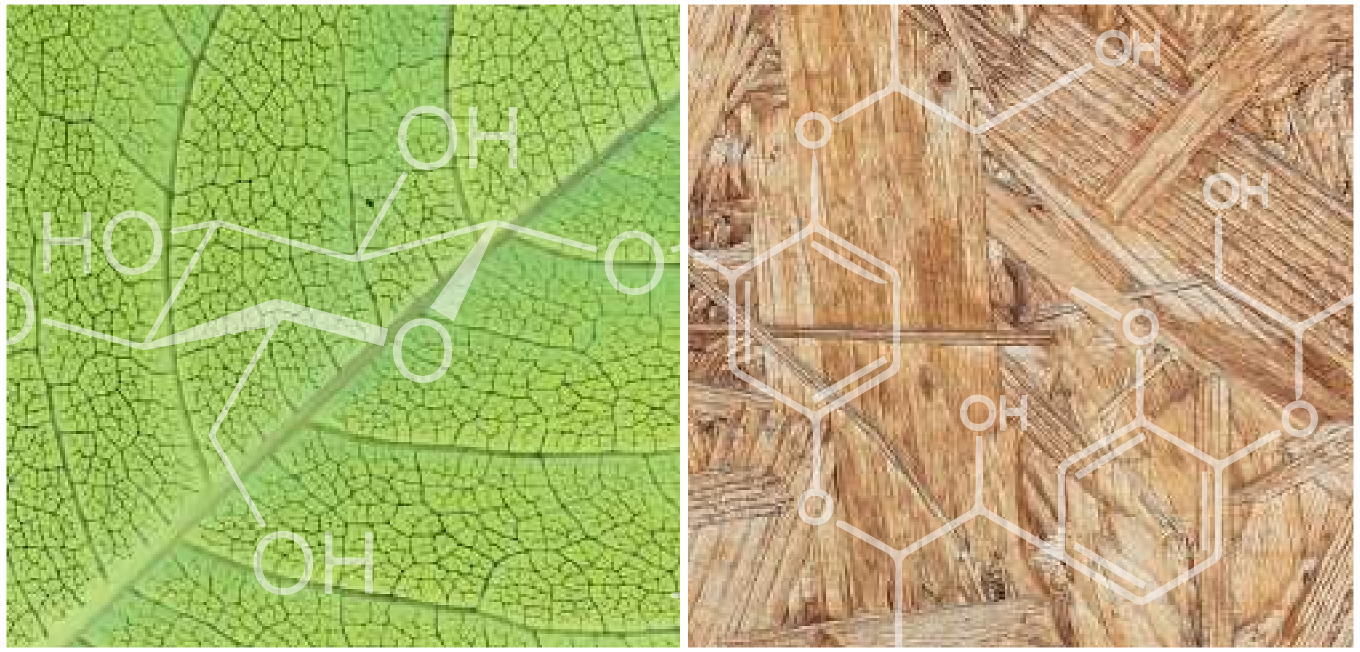
[2] CDD refers to ‘cumulative degree day’, or thermal time, and is a measure of how many degrees above 0 °C the soil is multiplied by the number of days.

4

Organic waste transformations during biological treatment

Organic waste transformations

- Organic wastes are composed of a variety of organic compounds, of which cellulose is the main chemical constituent of the organic fraction of municipal solid waste, followed by lignin and hemicellulose.
- A diverse range of micro-organisms are responsible for biodegrading organic wastes. Bacteria dominate in anaerobic digestion systems, whilst both bacteria and fungi are fundamental to the composting process.
- Lignin, which is the structural component in wood, is only degraded in aerobic (oxygen containing) environments, and through the action of some fungi and certain types of bacteria called actinomycetes.
- A process called humification occurs during composting, which results in the formation of stable organic matter when applied to soil.
- There is little scientific evidence of humification occurring during anaerobic digestion, which reflects both the process and the properties of digested wastes.



4.1

Organic waste composition

Before discussing what happens during anaerobic digestion (AD) and composting processes, it is worth briefly summarising the main chemical components present in organic waste, as it is these compounds that are transformed during treatment to help sustain microbial activity and create products.

Overall, it is thought that cellulose is the main chemical constituent of the organic fraction of municipal solid waste (MSW), followed by lignin and hemicellulose (Komilis & Ham 2003).

Although organic wastes vary significantly in their source, they broadly contain the main components listed in Table 3. The key exception here is lignin, which forms the hard-structural component of wood, and is only biodegraded in aerobic (oxygen containing) environments, such as during composting. This difference is important, as it affects the type and properties of organic matter in compost and digestate.

Table 3 – Main components of organic wastes (derived from Hubbe 2014)

Component	Description
Lignin	• A complex polymer forming the structural component in wood • Primarily present in woody green wastes. • Degraded slowly during composting • Not generally degraded anaerobically
Cellulose	• A polymer of glucose, present in plants (both food and green wastes) • A good source of energy and readily degraded during composting and AD • Source of energy
Hemi-cellulose	• A polymer of glucose and some other sugars present in plants (both food and green wastes) • A good source of energy and readily degraded during composting and AD
Proteins	• Nitrogen-rich molecules • Includes cell components and enzymes • Rapidly degraded during both composting and AD; a good source of nitrogen • Particularly predominant in food wastes
Carbohydrates	• Sugars and polysaccharides • A good source of energy and readily degraded during both composting and AD
Lipids	• Fats and oils, present as storage compounds and as components of cells • Rapidly degraded during both composting and AD; a good source of energy • Particularly predominant in food wastes

4.2

The role of micro-organisms

Both anaerobic digestion and composting are carried out by a range of different micro-organisms (microbes); summarised in Table 4. Microbes are single celled organisms, capable of living on their own. They feed by secreting enzymes outside of their cells and into the surrounding environment; these enzymes then digest the feedstocks, allowing the microbes to consume the breakdown products as food.

Other important chemical transformations also occur through the actions of extracellular microbial enzymes. Humification is one important process, which involves the chemical transformation of lignin into stable carbon compounds that are collectively called humus (see text box).

Table 4 – The main types of micro-organisms involved in organic waste treatment

Micro-organism	Description
Bacteria	These are microscopic single-celled organisms that have a primitive cellular structure. They are found all over the world in a diverse range of habitats, including the human gut, the deep oceans and soil. Bacteria are instrumental in both the composting and anaerobic digestion processes, although the types and ways in which they degrade organic wastes differ. Broadly speaking, bacteria can either be classified as: **Aerobic** – these require oxygen to breakdown feedstocks, creating new cells and metabolic by-products, as well as releasing carbon dioxide, water and heat. **Anaerobic** – these require oxygen free environments to breakdown feedstocks, creating new cells and metabolic by-products, as well as releasing carbon dioxide, water and usually methane.
Actinomycetes	These are a sub-class of bacteria that can form filaments. They are particularly important during the composting process, as some can withstand high temperatures and are able to partially degrade lignin.
Fungi	These are a group of multicellular organisms that are primarily responsible for global nutrient recycling and include both mushrooms and yeasts. Like bacteria, they are found all over the world; however, the majority are unable to tolerate high temperatures or extreme environments (unlike some bacteria). Fungi are the main decomposers of lignin and are therefore pivotal in the degradation and transformation of woody wastes. Wood-decay fungi can be classified according to the type of decay that they cause. Among the wood-decay fungi, the white-rot fungi are thought to be the main lignin degraders in the environment, although the brown-rot and soft-rot fungi are also thought to play important roles. Fungi are present during composting but are not though to be significant in commercial AD systems.

Micro-organisms are often classified according to the temperature ranges in which they prefer to grow:

Mesophilic – These are micro-organisms where the optimum temperature for growth is between 20-45 °C (warm environments)
Thermophilic - These are micro-organisms where the optimum temperature for growth is between 45 – 80 °C (hot environments)

Humification & humic substances

Humification is the process of forming **humic substances** from organic wastes. It involves a complex series of biochemical processes and occurs in soils and during the composting process. It is thought that the woody parts of plants (**lignin** as well as **cellulose** and **hemicellulose**) are the precursors of humic substances.

Humification is generally carried out by **fungi** (such as white and brown rot species), although some bacteria (especially the **actinomycetes**) may also be involved.

Humic substances are complex organic compounds that are broadly ill-defined; however, they are classified into one of three types based upon their properties (Aiken *et al.* 1985):

- **Humin (HU)** – this is not soluble in water at any pH, and is very stable, remaining in soils for many years;
- **Humic acids (HA)** – these are not soluble in water under acidic conditions, and are moderately stable in soil; and
- **Fulvic acids (FA)** – These are soluble in water under all pH conditions and are the least stable of the humic substances, having a faster turnover rate in soil that HU and HA.

Humification occurs during the composting process, and the extent to which it has occurred provides an indication of the maturity of the compost. Some researchers use a **Humification Index** (HI) to describe compost maturity:

Humification Index (HI) = Ratio between the concentration of humic acids and fulvic acids (CHA/CFA) expressed as a percentage of the total organic carbon

Humic substances are the main source of stable carbon in soil.

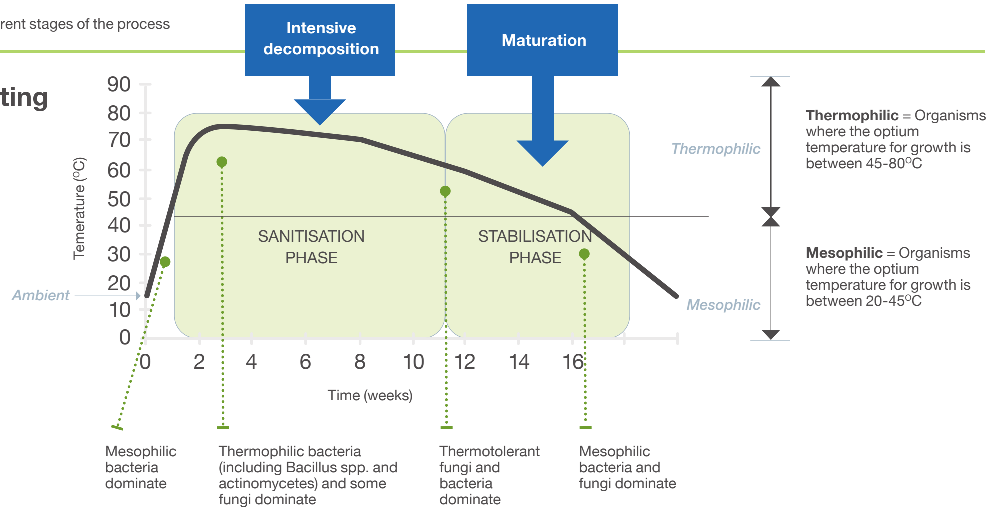
Broadly speaking microbes can be classed as either **anaerobic** (which mean that they can live and grow in the absence of oxygen) or **aerobic** (which means that they need oxygen to live and grow). The components listed in Table 3 can be degraded by both anaerobic and aerobic microbes, with the exception of lignin which requires oxygen.

Both AD and composting are dynamic environments which result in a succession of different microbial populations during the respective processes as the different components of the feedstocks are digested (Tiquia *et al.* 2002). These are summarised below.

4.3

Different microbes predominate at different stages of the process

Figure 6 – Stages of composting



Composting

The microbiology and biochemistry of composting is complex, and involves both bacterial and fungal microbial communities existing alongside each other. Overall, composting has been less well characterised than anaerobic digestion, with the main composting phases being described in physical terms, using temperature as an indicator of progress (Figure 6), although it is thought that degradation follows a first order kinetic model (Hamoda *et al.* 1998).

Initially, the temperature of the composting feedstock is in the mesophilic range (below 45 °C). Bacteria dominate during this phase (Albrecht *et al.* 2010), breaking down readily degradable compounds, including organic acids (which often causes the pH to drop). Heat energy is also released, causing the temperature to rise.

This increase means that only those microbes able to tolerate or thrive at higher temperatures survive. These are primarily species of thermophilic fungi and actinomycetes (Hubbe *et al.* 2010). Sophisticated DNA sequencing has shown that different communities of microbes dominate at different stages of the process, with a shift from bacteria to fungi as the compost matures (Hubbe 2014).

It is thought that cellulose and hemicellulose are the main sources of energy and are metabolised early in the composting process. Research has shown that almost all of the hemicellulose is degraded during composting, with cellulose reductions of between 54-91% being noted (Komilis & Ham 2003).

> ‘Cellulose is main source of energy; lignin the building blocks of humus’

As the temperature increases, thermophilic fungi and actinomycetes dominate and are responsible for the partial degradation of lignin. It is the breakdown products of lignin that are transformed into humic substances, through a series of complex reactions. Research has shown that adding lignin to composting feedstocks can increase humic acid formation (Smidt *et al.* 2008).

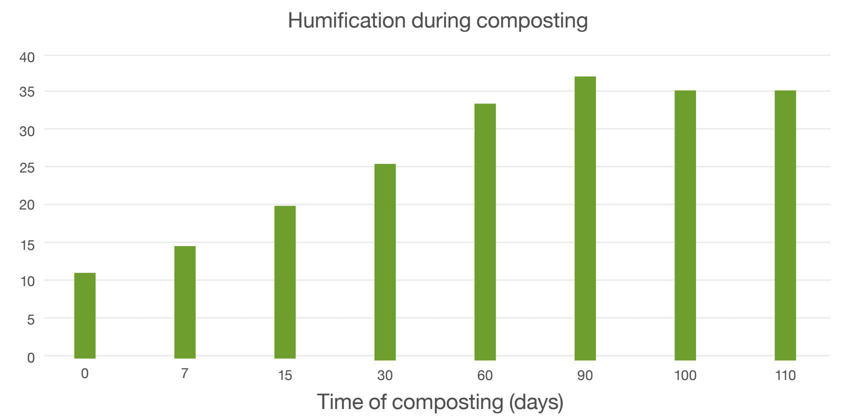
Overall, immature (fresh) compost tends to have a high concentration of fulvic acids (FAs) relative to Humic Acids (HAs). As the compost matures, the FA concentration either remains the same or decreases, but the level of HAs increases (Tuomela *et al.* 2000). This change in relative concentrations can be expressed as a Humification Index (see box).

The HI has been shown to increase during composting (Figure 7). This means that as composting progresses, humic compounds increase in structural complexity, which is an important factor when they are applied to soil. The relative concentration of humic acids is therefore an indicator of compost maturity.

There is also evidence to suggest that co-composting lignin-rich (woody) materials with an easily degradable carbon source, such as anaerobic digestate[3] or food waste, can increase humic acid formation (Smidt *et al.* 2004, Binner *et al.* 2011 & Prasad *et al.* 2012). The molecular mechanisms for this are unclear at present.

Binner *et al.* (2011) also suggested that composting processes with lower degradation rates produced composts with greater levels of humification, presumably because the microbes were better able to convert more of the feedstocks into humus. High rates of aeration were also thought to lead to low rates of humification; again, the molecular mechanisms behind this are unclear.

Figure 7 – Increase in Humification Index during composting
(Redrawn based on data published by Tejada *et al*. 2009)



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[3] However, there is also a note of caution: Binner *et al.* (2011) also found that digestate produced in a fermenter optimised for gas production was not as effective in producing humic substances when post-composted, compared with digestate produced following a shorter retention time. This was thought to be due to an absence of organic compounds necessary for humic acid formation.

4.4

Anaerobic digestion

In many respects, the microbiology and biochemistry of anaerobic digestion is better understood than that of composting. AD relies primarily upon bacteria which thrive in an oxygen free environment. There are broadly three main stages involved in the degradation of feedstocks and production of methane (see Figure 8).

It is thought that somewhere between 20-95% of the carbon in the feedstock is converted into methane and carbon dioxide during the AD process, with over 90% of volatile fatty acids, over 80% of hemicellulose, over 50% of cellulose and proteins being degraded (Möller, 2015). Notably, lignin is not degraded anaerobically, which is why green wastes are not generally suitable feedstocks for AD processes.

There is little scientific evidence of humification during anaerobic digestion; rather, the AD process has been shown to degrade both humic and fulvic acids at rates faster than they are formed (Li *et al.* 2017 & Marcato *et al.* 2009). Following AD, any partially degraded feedstocks, microbial biomass and non-degraded compounds remain as digestate. Any stable carbon compounds in digestate are therefore thought to have been concentrated due to mass loss during the AD process, rather than being formed *per se.*

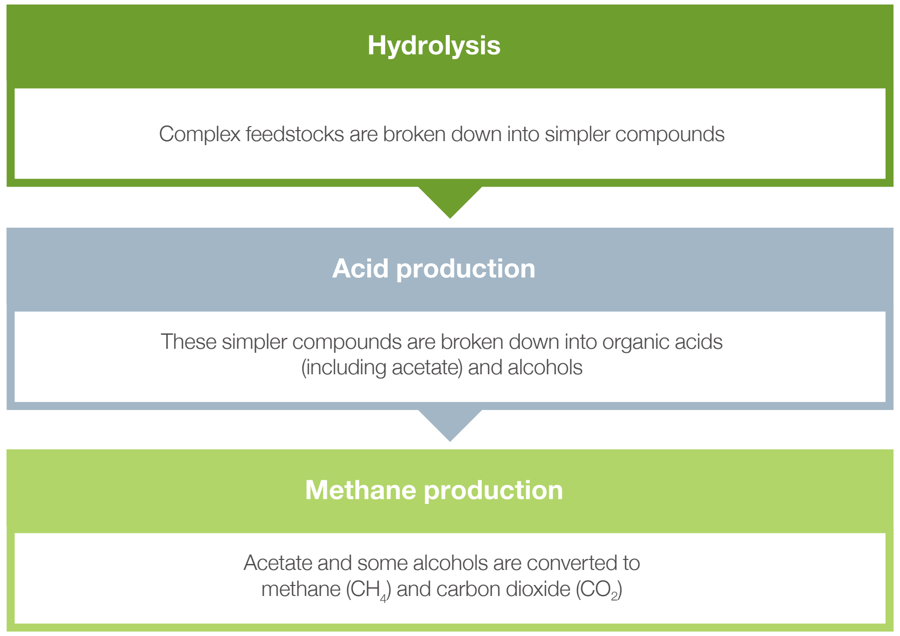


Figure 8 – **Main stages of the AD process**

Hydrolysis

Complex feedstocks are broken down into simpler compounds

Acid production

These simpler compounds are broken down into organic acids (including acetate) and alcohols

Methane production

Acetate and some alcohols are converted to methane (CH_4) and carbon dioxide (CO_2)

5

The benefits to soil of organic amendments

BENEFITS OF ORGANIC AMENDMENTS

- Compost can be classified as an organic soil improver, as it contributes towards a soil's organic matter content.
- Digestates can be classified as an organic fertiliser, as their main function is to supply plant nutrients.
- Greater amounts of carbon remain in the soil when organic wastes are composted, rather than applied directly.
- Organic matter in compost is further transformed through soil microbes into more stable forms of carbon in soil.
- Compost has the potential to sequester carbon in soil:
  - Studies have shown that over a period of 4-12 years between 11% - 45% of the organic carbon applied to soil as compost remained as soil organic carbon.
  - Soil organic carbon increases of between 50-70 kg C ha^{-1} yr^{-1} t^{-1} dry solids applied as compost are possible.
  - Every tonne of soil organic carbon holds the equivalent of about 3.67 tonnes of atmospheric carbon dioxide.
  - 1 tonne (fresh mass) of green waste derived-compost applied to soil over one hectare (10,000 square meters) results in a net CO_2-eq saving of 143 kg ha^{-1} $year^{-1}$ due to the increase in soil organic matter alone.
  - The main benefits to soils are realised in the first 20 years until a new organic matter equilibrium is reached.
- Repeated compost application increases soil aggregate stability and soil pores, reduces compaction and increases water holding capacity.
- Applying compost to soil has been shown to increase soil microbial biomass and microbial activity, and build up a pool of plant nutrients.
- The long-term benefits to soil of anaerobic digestate are less clear cut than those of compost, and it is thought that it has a negligible effect on soil organic matter in the long term.
- Increases in soil microbial activity have been measured following digestate application.
- The significant benefit of applying digestate to soil is due to its high nutrient content.

Section 3 introduced the importance of soil and its organic matter content. This section summarises research assessing the impact of adding organic matter amendments, such as compost and digestate, to soil. It is the subject of a great deal of scientific scrutiny, so we have endeavoured to summarise this into an easy to read format without compromising academic integrity.

5.1

Classifying organic amendments

Compost and anaerobic digestate differ in their chemical composition, which is due to the different types of feedstocks from which they have been derived (in particular, whether or not they contain lignin) and the biological treatment processes themselves (i.e. whether it has been an aerobic and/or anaerobic process). The combination of these two factors means that both compost and digestate differ in the levels of humic substances and the type and availability of plant nutrients they contain. These differences therefore affect the ways in which these organic amendments behave when applied to soil.

Veeken *et al.* (2017) reviewed biochemical data obtained from a range of organic amendments, including compost, digestate, farmyard manures /slurries. The authors differentiated between organic inputs that contribute towards a soil's organic matter content and those that were primarily fertilisers (due to their nutrient content).

They used the term '**effective organic matter**' (EOM), which they defined as "the organic matter that is still available after one year after incorporation in the soil. The remaining percentage of organic matter is also referred to as humified (residual) organic matter".

The EOM was calculated based on the organic matter content and the humification coefficient (HC), where the HC was defined as the fraction of effective organic matter to total organic matter. The ratio of EOM to both mineral nitrogen and phosphorus were then calculated for the different organic amendments and plotted on a graph (Figure 9).

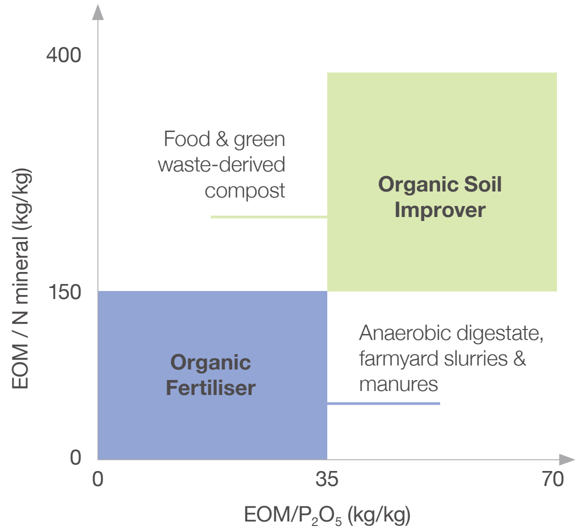
They suggested that:

- "An organic soil improver should contain a high level of EOM to contribute to soil organic matter and should be low in nutrients as it is not a fertiliser; and
- For an organic fertiliser it is the other way around: high in nutrients and low in EOM".

On the basis of this classification, and for the purposes of quantifying soil benefits:

- Composts can be classified as an organic soil improver; and
- Digestates can be classified as an organic fertiliser.

Figure 9 – Classification of organic amendments as either an organic soil improver or organic fertiliser based on the ratio of EOM to nutrients (N & P) (re-drawn from Veeken *et al.* 2017).



5.2

Benefits of applying compost to soil

5.2.1 Soil organic matter content

A number of studies have reported the benefits to soils of compost additions over periods of years, some of which are summarised in Table 5.

Table 5 – Summary of selected studies demonstrating beneficial effects of compost application to soil

Compost Type	Soil Type / Crop System	Time Period	Observed Effect(s)	Reference
Rice-straw compost	Rice – wheat cropping	10 years	Increase in total SOC (~29%) and labile carbon following application rates of 4 & 16 tonnes / ha / year compared with control. Authors noted that increasing the labile carbon content affected the soil's mean weight diameter, which is an indication of soil aggregate stability.	Sodhi *et al.* 2009
Not stated	Entisol in Mediterranean Turkey Annual application of compost to soil just before sowing range of crops over period 1996 and 2010	14 years	Compost application of 25 tonnes / year resulted in an increase in SOC of 7.49 tonnes / ha over the 14-year period across the 0-0.30 cm horizon and total soil N of 0.29 Mg ha^{-1}.	Ortas *et al.* 2013
Dairy-waste compost	Not stated	5 years	C pool was enhanced by 115% It was calculated that the carbon stored in the soil organic matter accounted for about 11% of the total amount of C applied.	Quoted in: Diacono & Montemurro 2010
Food & lignocellulose-derived compost	Silty-clay (Italy) cultivated with Maize	6 months (150 days)	Compost was applied at two rates: • 50 tonnes / ha • 85 tonnes / ha Carbon sequestration rates between 617 – 623 g C / kg compost. 40% - 53% of the total carbon added was retained in the soil. Linear response between application rate & C degradation and retention. Suggested labile carbon was rapidly mineralised.	Adani *et al.* 2009
Seaweed–fish waste compost	Humic cambisol (greenhouse)	110 days	Compost added to soil at two rates: 30.5 and 50.84 g dry compost / kg soil. Two rates of C mineralisation observed; each having different rate constants: • 20% was in easily available form (k = 0.029) • 80% mineralised slowly (k = 0.005)	Illera-Vives *et al.* 2015
Green waste compost, Vegetable, fruit & garden waste compost, and spent mushroom compost.	Sandy loam	21 weeks	Only between 1.8% and 8.8% of the C was mineralised at the end of the experiment.	De Neve *et al.* 2003
Crop residue, manure & phosphate fertiliser compost	Argissolo amarelo (citrus orchard in Northern Brazil)	16 months	Increase in SOC in 0-0.15 m depth of 37%. Addition of mineral fertilisers increased SOM decomposition rate.	Moura *et al.* 2017
Green waste compost	Two experimental sites in the UK: sandy/light and medium (heavy)	9 years	Increase in SOM content by ~24% (equivalent to an additional 8-10 t/ha SOM in the topsoil) compared to control when green waste compost was applied at a total loading rate of 47-49 t organic matter/ha over the trial period. This was a similar increase in SOM to that observed for farm-yard manure over 20 years.	Bhogal *et al.* 2016
Poultry manure compost	Two soil types: silt loam and silty clay loam	19 years	Compost was applied at a rate of 4 t / ha prior to sowing with maize/winter cover crop followed by tomato/winter cover crop rotations in alternate years. Increase in SOC stock of: • 5.31 tonnes C / hectare in the 0-15 cm layer; and • 2.59 tonnes C / hectare in the 15-30 cm layer • 21.8 tonnes C / hectare across 0-200 cm layer Increases in SOC were also noted in the 30-200 cm later, which was not observed with other treatments. Increase in SOC due to compost & winter cover crop.	Tautges *et al.* 2019

In addition, the following publications also summarise measured increases in soil organic matter content following repeated applications of organic amendments:

- Beneficial Effects of Compost Application on Fertility and Productivity of Soils (Amlinger *et al.* 2007);
- Sustainable Compost Application in Agriculture (ECN 2017); and
- Soil Biology and Soil Health Partnership Research Case Study - Testing the effect of organic material additions on soil health (AHDB 2019).

Overall, evidence suggests that a greater amount of carbon remains in the soil when organic wastes are composted, rather than applied directly. For example, in an experiment comparing the effects of raw dairy manure and composted manure on soil carbon, 36% of the applied carbon in the compost remained in the soil after four years compared with 25% of the manure carbon (Eghball 2002). Mature composts are also thought to be better at increasing soil organic matter levels than fresh or immature composts due to the higher concentration of stable carbon (Adugna 2016).

This was also noted by UK researchers (Bhogal *et al.* 2016), who monitored the effect of different organic wastes on the light organic matter fraction (LFOM)[4] in soil. They found that application of compost increased the LFOM, although a similar increase was not observed following the application of liquid organic materials (anaerobic digestate and livestock slurry).

In a recent paper, Tautges *et al.* (2019) demonstrated that application of compost in conjunction with winter cover crops significantly increased the soil organic carbon content in the 0-200 cm horizon over a 19-year period. This increase was not observed with conventional fertilisers and winter cover crops alone, suggesting that the compost was responsible for the SOC increases, especially in the deeper soil layers (60-200 cm). This increase in SOC in the deeper soil layers is though to be important for carbon storage.

It is thought that the maturity of compost and the feedstocks from which it is derived influences the type and proportions of humic substances it contains. Once applied to soil, these are converted into more stable forms through the action of soil microbes. Research has suggested that humic acids in compost are in so-called 'neoformation', and when added to soil, they can be incorporated into the soil's humic acid structure (Velasco *et al.* 2004).

Following application of compost to soil, researchers traced the incorporation of carbon in compost into the stable humin fraction in soil. Notably, the humin content increased as the rate of compost application increased (Lima *et al.* 2010).

> 'Organic matter in compost is further transformed through soil microbes into more stable forms of carbon in soil'

A comprehensive review of the long-term effects of organic amendments on soil fertility by Diacono & Montemurro (2010) concluded that:

> "Long-lasting application of organic amendments increased [soil] organic carbon by up to 90% versus unfertilized soil, and up to 100% versus chemical fertilizer treatments".

5.2.2 Potential for carbon sequestration

There is currently a great deal of interest in the potential for soils to sequester carbon and therefore to help mitigate climate change, and there are a number of good sources of information that summarise this well, including:

- The **European Commission's Climsoil project** (http://ec.europa.eu/environment/soil/review_en.htm); and
- The **FAO's Soil Portal** (http://www.fao.org/soils-portal/en/)

Soil Carbon Sequestration

Soil carbon (C) sequestration can be defined as **any persistent increase in soil organic carbon originated from removing carbon dioxide from the atmosphere** (Torri *et al.* 2014). Soil C sequestration capacity is therefore a function of the soil's ability to retain and stabilise carbon.

Humification of organic wastes is one way in which carbon can be sequestered in soil, although other mechanisms, such as the formation of carbonates, application of biochar and formation of clay-humus complexes can also play a role (Diacono & Montemurro 2010).

The potential for a soil to sequester carbon is not finite, as an equilibrium will be reached where the rate of soil organic carbon formation is equal to its degradation, meaning that its concentration remains stable.

The benefits of soil carbon sequestration to mitigate climate change were reviewed by Powlson *et al.* (2011). The authors suggested that the net benefit of applying organic residues to soil depended upon their alternative fate. They noted that if "the alternative disposal method is burning, application to soil where at least part of the residue C will be retained will be an improvement from the viewpoint of climate change mitigation. Similarly, if the alternative is disposal to landfill, soil application will generally be of benefit." They cite the example of green waste compost, where the disposal and subsequent decomposition in a landfill will result in methane generation. Unless the methane is captured and used as an energy source "application to land will represent an 'avoided emission' of methane in addition to a degree of soil C sequestration".

Factors such as soil type, climatic conditions, land management practices and soil clay, as well as the degree of humification of organic amendments, influence the rate at which organic matter breaks down or is transformed into more stable forms when applied to soil (Torri *et al.* 2014 & Schmidt *et al.* 2011). This makes estimates of carbon sequestration potential very difficult. In addition, deriving data from scientific papers is problematic, as authors do not always state: the type or stability / maturity of the compost; the soil depth; or, whether the compost was spread on the surface or tilled into the surface layers. The latter is an important point, as incorporation into soil can affect the rate of surface oxidation or complexation with inorganic components, such as clay minerals, in the soil.

It is thought that carbon in compost is mineralised at two different rates, each with its own decay rate constant (Adani *et al.* 2009, Illera-Vives *et al.* 2015 and Pedra *et al.* 2007). It is thought that:

- There is a readily degradable fraction (with one estimate of about 20%) that decays rapidly following exponential kinetics; and
- A more stable fraction that is mineralised slowly, decomposing linearly.

Overall, it is thought that the rate of mineralisation is highest during first few days following application to soil, which then decreases until reaching a stable rate.

Experiments published by a number of researchers have also shown that more carbon is retained in the soil when organic wastes are composted rather than when they are applied directly without aerobic treatment (e.g. composted cattle manure vs. raw manure); see for example, Eghball (2002), Powlson *et al.* (2012), Bhogal *et al.* (2016) and Peltre *et al.* (2017). This is due to the higher levels of humification that are formed during composting, and the decomposition and subsequent loss of the more volatile carbon compounds during processing.

Nevertheless, increases in soil organic carbon levels have been measured following compost application, as shown in the example in Figure 10.

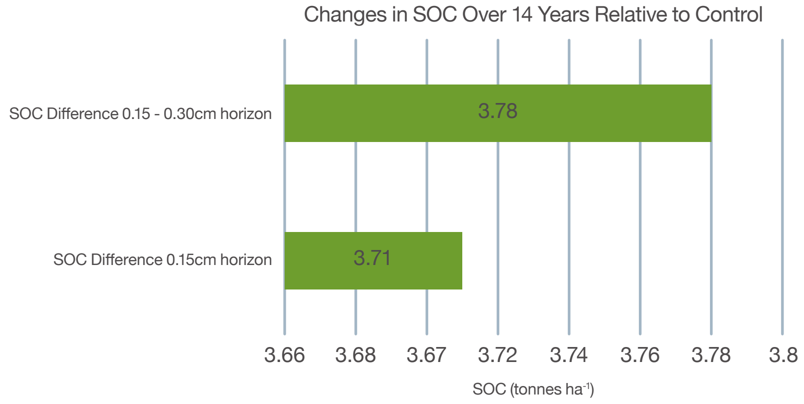


Figure 10 – Increases in measured SOM following compost addition over 14 years (based on data published by Ortas et al. 2013)

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[4] The LFOM is thought to be a transitional pool of organic matter within soils, somewhere between fresh residues and humified stable organic matter.

Table 6 – Summary of C sequestration potential following compost application to soil

Compost Type	Soil Type / Crop System	Time Period	C sequestered	Reference
Green waste derived compost	Four sites in the UK	5 & 8 years	Mean annual increase in SOC of **60 ± 10 kg C ha^{-1} yr^{-1} t^{-1} dry solids** Similar to a rate of 70 kg C ha^{-1} yr^{-1} t^{-1} dry solids by Ros *et al*. 2006 (quoted in Powlson *et al*. 2012) in Austria over 12 years. **23% of the organic C in the compost remained in the soil.** (cf. about half as much carbon was stored when farmyard manures were applied directly to soil)	Powlson *et al*. 2012
Dairy-waste compost	Not stated	5 years	Carbon stored in the soil organic matter accounted for about **11% of the total amount of C applied.**	Quoted in: Diacono & Montemurro 2010
Cattle manure compost	Silty clay loam, Nebraska, USA	4 years	**36% of the organic carbon in compost remained** in the soil at the end of trial (cf. 25% of C applied as manure).	Eghball 2002
Green waste compost	Two experimental sites in the UK: sandy/light and medium (heavy) with a prior history of organic amendment application	9 years	**20-24% of the organic carbon was retained in the soil** (cf. 12% farm-yard manure)	Bhogal *et al*. 2016
Garden & household waste anaerobically digested & post-composted	Sandy loam, Denmark	12 years	**45% of the organic C remained in the plough layer after 12 years** of annual application (cf. 38% of C for sewage sludge and 21% for cattle manure).	Peltre *et al*. 2017
Poultry manure compost	Two soil types: silt loam and silty clay loam	19 years	Increase in SOC of 2.22 tonnes / hectare / year following compost applied at 9 tonnes / hectare (compared to conventional treatment). Difference of 3.5 times the conventional system. Application of 700–800 kg C /ha/ year increased soil C by 12% over 19 years. Rate of increase of 6.6‰ per annum. Increase in SOC levels in the subsoil noted.	Tautges *et al*. 2019

The data in Table 6 therefore suggest that:

- Over a period of **4-12 years** between **11% - 45%**[5] of the organic carbon applied to soil as compost remained as soil organic carbon; and
- Soil organic carbon increases of between **50-70 kg C ha^{-1} yr^{-1} t^{-1} dry solids** applied as compost are possible.

These ranges are summarised in Table 7.

Table 7 – Scenario ranges of organic carbon remaining in soil over time (rounded to nearest integer and based on the research presented in Table 3)

	Time (years following compost application)	% organic carbon remaining in soil
Minimum	4	11
Maximum	12	45
Median	8	24
25 percentile	-	21
75 percentile	-	33

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[5] This accords with Powlson *et al.* 2011, who suggested that, under temperate climate conditions, about 33% of plant material remains in the soil after one year.

In general, the **organic carbon content of compost is about 17-18% (on a dry matter basis) and about 30% organic matter (on a dry matter basis)**; see for example Bhogal *et al*. 2016. This is significant in terms of climate change, as it is thought that:

Every tonne of soil organic carbon holds the equivalent of about 3.67 tonnes of atmospheric carbon dioxide (GWA 2018).

Based on published research, Powlson *et al*. 2012 calculated the net changes in greenhouse gas emissions resulting from the application of various organic materials (Table 8). These calculations not only take into account the sequestration potential due to increasing soil organic carbon, but also avoided N_2O emissions by offsetting the use of inorganic fertilisers.

Table 8 – Calculated net changes in greenhouse gas emissions resulting from the application of selected organic materials (based on data published by Powlson *et al.* 2012)

Organic material	Application rate	Net CO_2-eq change due to increase in soil organic carbon	Net CO_2-eq change due to nitrogen savings (savings from manufacture & changes in N_2O)	Total net CO_2-eq saving	Net CO_2-eq saving / tonne or m^3 (fresh mass) due to increase in SOC	Total net CO_2-eq saving / tonne or m^3 (fresh mass)
	tonnes or m^3 (fresh mass) / hectare	CO_2-eq (kg ha^{-1} yr^{-1})				
Cattle manure	42	2310	290	2600	55	62
Dairy slurry	83	1100	120	1220	13	15
Green compost	36	5130	110	5240	143	146

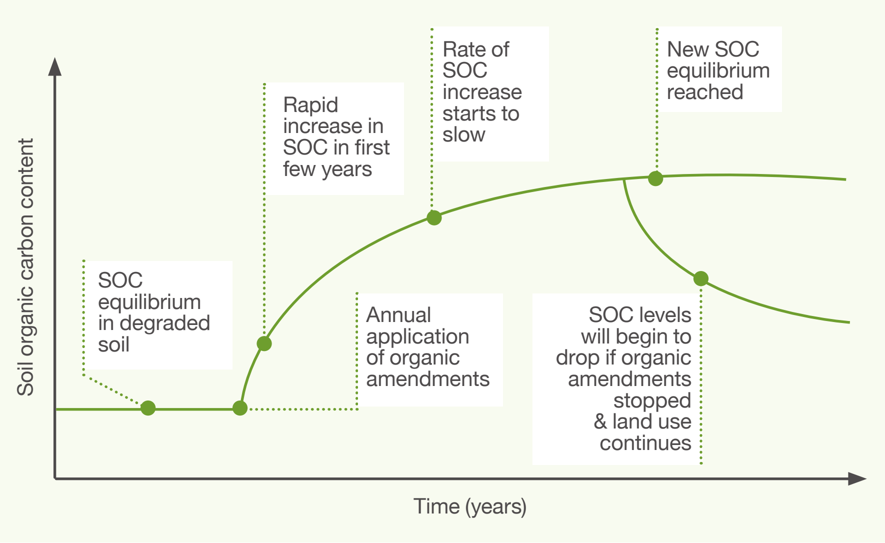
The data published by Powlson *et al*. (2012) suggest that:

1 tonne (fresh mass) of green waste derived-compost applied to soil over one hectare (10,000 square meters) results in a net CO2-eq saving of 143 kg/ha/year due to the increase in SOM alone (excluding fertiliser offsetting).

Additionally, it has been shown that applying compost to soil can also result in a transient increase in methane uptake by the soil, which confers additional benefits in terms of greenhouse gas emission reductions (Ho *et al*. 2015). Increases in sub-soil SOC is also though to protect it against degradation (Tautges *et al*. 2019).

Despite the benefits of applying compost to soil, the increase in soil organic matter does not increase linearly. It is thought that the main benefits to soils are realised in the first 20 years or so, with decreasing benefits following application as a new equilibrium is reached; see Figure 11. This has been noted in long-term field experiments using farmyard manures, which have shown that the rate of SOC increase starts to reduce as a new equilibrium is approached (Powlson *et al*. 2012).

Figure 11 – Schematic diagram showing changes on SOC content following compost application



Powlson *et al*. (2011) cite the limitation of soil carbon sequestration:

- The amount of C locked up is finite: the increase in SOC content ceases as a new equilibrium value is approached; and
- The process is reversible: the change in land management[6] leading to increased C in soil or vegetation must be continued indefinitely to maintain the increased stock of SOC."

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[6] In addition, changes in land management practices may also change fluxes of nitrous oxide or methane, both of which are powerful greenhouse gasses.

Soil clay

Clay is composed of certain types of minerals, including hydrous aluminium phyllosilicates. It can also be associated with traces of quartz, metal oxides, organic matter and certain metals, including iron and magnesium. It has a very fine texture, which gives it its plastic nature when wet; however, it also sets very hard when dry.

Clay is thought to bind humic substances to form a clay-humus complex, and this is thought to increase the stability of the organic matter and increase its resistance to biodegradation (Amlinger *et al.* 2007), although the precise mechanisms for this are not fully understood. Experiments suggest that as soil clay content increases, soil microbial biomass carbon also increases (Pedraa *et al.* 2007); whilst a strong correlation between soil carbon and the percentage of clay has been observed.

Co-composting biodegradable waste with clay has been practiced traditionally in China (King 1911) and recent scientific studies have suggested that co-composting organic amendments with clay materials is effective in stabilising the carbon (C) in soil. This was demonstrated by Bolan *et al.* (2012) who concluded that: "Stabilization of C in composts using clay materials not only maintains their value in improving soil quality … but also would add to the long-term soil C pool".

Additionally, evidence is starting to emerge that co-composting biodegradable waste with alkaline materials can also increase carbon stabilisation (Chowdhury *et al.* 2016).

Transport carbon emissions

As most compost is transported by road to the site where it is applied, it is generally recognised that transport distances should be minimised in order to reduce carbon dioxide emissions emanating from diesel/transport fuel. However, calculations carried out by Smith & Smith (2000) suggested that **"fuel [carbon] C costs of transporting resources are much lower than the C benefits of agricultural mitigation options".**

The researchers calculated the carbon mitigation potential of applying manure and sewage sludge to arable land (European-wide calculations) and the associated carbon releases of moving the organic materials per kilometre. Overall, they calculated that the emissions from transporting these materials by 100 km would release the following:

- **Sewage sludge** – less than 1% of the C benefit from mitigation; and
- **Animal manure** – about 30% of the C benefit from mitigation.

Overall, they concluded that: **"transport distances under 100 km are unlikely to negate the net C benefit of the options examined"**.

5.2.3 Soil structure

Soil structure is determined by the way its solid parts bind together. It affects the pores (air spaces) in the soil, and therefore impacts on its capacity to retain moisture, allow air to diffuse and grow plants. In general, cultivated soils such as those on which arable crops are grown, tend to have poor structure as a result of compaction caused by ploughing and loss of organic matter.

Improvements in soil organic matter go hand-in-hand with improvement in a soil's structure; hence research that has shown addition of organic amendments (such as compost) not only increase the soil's organic carbon content, but also improve its structure. Soil aggregation is important as it is thought to increase the stability of the carbon and reduce its turnover in soil. In addition, recent research has suggested that soil pores may have an important role to play in stabilising soil carbon; meaning that increasing the number of soil pores may also increase a soil's capacity to retain new carbon inputs (Kravchenko *et al.* 2019).

Compost additions to soil have been shown to:

- Improve soil aggregation and lead to carbon sequestration in a Mediterranean soil (Ortas *et al.* 2013). The experiments also showed that aggregate size and soil organic carbon associated with aggregates increased with compost and organic manure treatments, with the SOC being associated with stable aggregates. The SOC was associated with larger aggregates (0.5 – 1.0 mm) than aggregates smaller than 0.25 mm.
- Research summarised in a review by Diacono & Montemurro (2010) suggested that bi-annual applications of municipal solid waste compost increased soil aggregate stability by 29% relative to the control.
- Diacono & Montemurro also summarised published research that suggested long term application of organic amendments, such as compost, reduced bulk density of agricultural soil on average by 15%.
- Data derived from a number of sites in the UK suggested that a reduction in soil bulk density of 5% was observed following repeated application of green waste-derived compost to arable soil over 9 years (Bhogal *et al*, 2016)

Repeated compost application increases soil aggregate stability and soil pores, and reduces compaction

Reducing bulk density also improves the workability of the soil, thereby reducing frictional resistance when ploughing.

5.2.4 Soil water holding capacity

Organic matter is thought to increase a soil's water holding capacity through two important mechanisms

- Due to its hydrophilic (water attracting) biochemistry; and
- Due to its effect on soil aggregates and increase in soil porosity, which means that there are more channels in the soil in which to hold water.

Available water capacity (AWC; see box) is the metric commonly used to measure a soil's ability to hold water.

A review carried out by Huntingdon (2007) suggested that soil texture (i.e. its relative composition of sand, loam and clay) significantly affected the relationship between soil organic matter content and its AWC. This means that depending upon the soil type, changes in the SOM content have a differential impact on its AWC. Overall, medium- to coarse-textured soils show greater increases in AWC due to increasing SOM content compared with finer-textured soils.

Huntingdon reviewed a number of publications and suggested that there was an average change in AWC of **1.1 cm^3 water/100 cm^3 soil for a 5% increase in SOM** (where the initial SOM concentration was in the range of 2–4% by weight). However, he also noted that some studies found no relationship between SOM content and its AWC; an observation also noted by Bhogal *et al.* (2016) and Minasny & McBratney (2018).

A review carried out by consultants on behalf of the European Commission (BIO Intelligence Service 2014) suggested that a 1% increase in SOM increases the AWC by more that 1.5-2%.

More recently, a meta-analysis of data by Minasny & McBratney (2018) suggested that: **"a 1% mass increase in soil OC on average increased available water capacity by 1.16%, volumetrically".**

Measuring soil water holding capacity

Soil scientists use the term **'Available Water Capacity'.** This is defined as:

Available Water Capacity (AWC) = The amount of water (cm^3 water/100 cm^3 soil) retained in the soil between the **Field Capacity' (FC) and the Permanent Wilting Point (PWP).**

The **field capacity** is the volumetric fraction of water in the soil at soil water potentials of 10–33 kPa.

The **permanent wilting point** is the volumetric fraction of water in the soil at soil water potential of 1500 kPa.

5.2.5 Soil biology

The repeated application of organic amendments (including compost) to arable lands has been shown to improve soil biological functions. This includes effects on the soil's indigenous microbes, as well as invertebrates such as worms.

Although compost amendments will act as a source of additional micro-organisms, it is thought that the main effects on soil biology are due to the carbon and nutrients present in the compost, which provide a food resource for those microbes and invertebrates already present in the soil. Different types of organic matter are thought to differentially affect soil microbial activity (Peltre, 2017).

Research has shown that applying compost to soil can affect soil micro-organisms in two important ways (Diacono & Montemurro, 2010 & De Araújo *et al.* 2010):

- It increases the soil microbial biomass, which means that there are more microbes present; and
- It increases the activity of the microbes, as measured using either indicator enzymes or respiration techniques.

This is important for a number of reasons, as it:

- Improves nutrient recycling;
- Increases the resistance of crops to diseases (pathogen suppression); and
- Improves soil structural stability due to the formation of exogenous polysaccharides (which tend to act as a glue, increasing soil stability) and humic substances.

Example research findings are summarised in Table 9.

Table 9 – Effect of compost addition on soil biological properties

Compost Type	Soil Type / Crop System	Time Period	Observed Effect(s)	Reference
MSW-derived compost	Sandy texture and low organic matter content, Spain	9 years	Compost applied at 20 & 80 tonnes / ha. Increase in soil microbial biomass of 10 and 46% at the 20 & 80 t/ha rates, respectively. Increase in oxidoreductase enzymes (e.g. dehydrogenase and catalase), increased by 730 (C20) and 200% (C80), respectively (compared with control). Attributed to microbial stimulation by the organic carbon.	Garcia-Gil *et al.* 2000
MSW-derived compost Review paper	Numerous	-	Authors noted that: "Soil system receiving more organic matter tends to harbour higher levels of soil [microbial biomass carbon] with greater microbial activity". The microbial biomass carbon, soil respiration activity and enzyme activities were found to increase with the increasing doses of MSW compost. MSW compost had a positive effect on the activity of enzymes related with C, N & P cycles.	De Araújo *et al.* 2010
Literature review of the disease suppression capability of composted materials in horticulture, agriculture and turf grass applications	Numerous	-	Evidence of suppression of soil-borne diseases by compost. In particular: Significant disease suppression was found at compost inclusion rates of < 20% v/v in soil; however, high application rates needed to show effects in field. Most research has been conducted in containers. Suppression of the following noted with green waste compost: • Wilts and rots caused by *Fusarium oxysporum formae* speciales; • Damping-off caused by *Rhizoctonia solani* (but less reliable); • Dollar spot in turf (caused by *Sclerotinia homoeocarpa)* by using compost as a top-dressing.	Noble *et al.* 2006
Green waste compost	Two experimental sites in the UK: sandy/light and medium (heavy) with a prior history of organic amendment application	9 years	Increase in soil microbial biomass carbon by ~17% and soil microbial biomass nitrogen by ~23% (data extrapolated from bar graphs). Increase in earthworm numbers observed.	Bhogal *et al.* 2016

The data summarised in Table 9 suggest that following application of compost to soil:

- Increases of up to 100% in soil microbial biomass have been measured experimentally
- Increases in enzyme activities associated with carbon, nitrogen and phosphorus recycling have been measured;
- Increases in earthworm densities have been recorded; and
- Green waste-derived compost can be effective in suppressing horticulturally significant soil-borne plant pathogens; however, high rates of application have been needed to show effects in the field.

5.2.6 Soil fertility

As compost and many other organic amendments contain nitrogen, phosphorus and potassium, it comes as no surprise that repeated applications of these materials can improve soil fertility and hence its ability to sustain plant growth. There are numerous examples of published research showing the fertilisation effects of compost additions and quantifying the effect on a wide range of crop yield (see for example: Amlinger *et al.* 2007; ECN 2017; Tautges *et al.* 2019; WRAP 2007 & 2019).

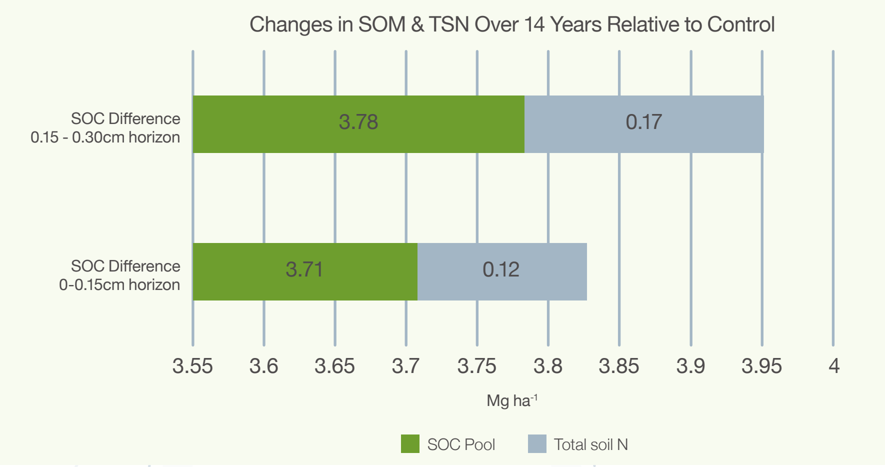
In their review, Diacono & Montemurro (2010) suggested that repeated compost applications can increase soil organic nitrogen content by up to 90%. Ortas *et al.* (2013) also measured increases in total soil nitrogen and soil organic carbon following long term application of compost to a Mediterranean soil; the data have been reproduced in Figure 12.

This nitrogen is not available in a readily available mineral form (as would be the case with a conventional inorganic fertiliser), rather it forms part of the soil organic matter and is released gradually over time through the action of soil microbes. Nitrogen mineralisation rates can vary depending upon the organic amendment, soil type, climate etc.; however, it is thought that somewhere between 0-20% of the total nitrogen content will be mineralised and made available for plant uptake in the first year following application (Prasad, 2009).

This slow release of nitrogen, which is bound up as part of the soil's organic matter, means that it is far less likely to leach into groundwater and cause pollution, unlike mineral fertilisers. It also means that repeat applications of compost can build up a 'nutrient bank' and improve a soil's overall fertility. Diacono & Montemurro (2010) suggest that there is "a significant residual effect from the cumulative applications which becomes visible later after 4–5 years, resulting in deferred higher N availability and yields".

Regular application of compost to soil can build up a pool of nutrients, especially nitrogen, which increases the soil's fertility and improves its ability to grow crops

Figure 12 – Increase in total soil nitrogen following application of compost to soil over 14 years (Based on data published by Ortas *et al.* 2013)



5.2.7 Soil cation exchange capacity & pH

Compost in general, and humus in particular, have the capacity to bind cations (positively charged ions) because they have slight negative charges on their surface. This is termed the cation exchange capacity (CEC) and is important in soil, as it helps bind major plant nutrients such as calcium, magnesium, potassium and sodium. Applying compost to soil and increasing the soil organic matter content has been shown to increase its CEC, which helps act as a nutrient buffer (Wallace & Brown, 2004; Amlinger *et al.* 2007; Adugna, 2016).

In addition, because most composts tend to be slightly alkaline, they can help prevent acidification of soil over time. Farmers add lime to soil to increase its pH[7] and help improve crop nutrient uptake. Compost can partially offset the use of lime, having a neutralising value of up to 15% of lime on a dry mass basis (Amlinger *et al.* 2007; Earthcare Technical Scotland, 2011; Adugna, 2016).

5.2.8 Soil quality & contamination

Organic amendments, including compost, contain substances that may adversely affect soil quality. Some of these are present naturally in soils, such as heavy metals, whilst some are of manmade origin, such as plastics, glass, metals and some organic compounds. They are generally called contaminants or impurities.

Some heavy metals, such as copper and zinc, are plant micronutrients and are needed in low concentrations to support healthy plant growth. However, when high concentrations are present in soil, they can adversely affect plant growth, crop quality and soil micro- and macro-organisms.

Following a review of published literature, Diacono & Montemurro (2010) suggest that when high-quality compost is applied to soils over long periods of time there is no tangible evidence demonstrating negative impacts of heavy metals in the soils.

Repeat applications of quality compost and digestate at a number of sites across the UK also suggested that there was no effect on soil total metal and organic compound contaminant concentrations or crop metal concentrations (Bhogal *et al.* 2016).

Smith (2009) has suggested that compost can reduce the solubility and bioavailability of heavy metals in soil, due to complexation with organic matter. He also suggested that there is no evidence of heavy metal release following degradation of organic matter in soil. Overall, he concluded that: "composting processes overall are likely to contribute to lowering the availability of metals in amended soil compared to other waste biostabilisation techniques".

As repeated application of contaminated compost has the potential to accumulate contaminants in soil, it is of concern to environmental regulators, soil scientists, land managers and agronomists. Precautionary concentration limit levels have been set for a range of contaminants in national and European-wide compost quality standards (see for example, the European Compost Network's Quality Assurance Scheme ECN-QAS), which are intended to protect soil. The benefits to soil of compost and digestate application described in this report assumes that they have been derived from separately collected bio-wastes (not mixed residual wastes) and contain low levels of contaminants, including heavy metals.

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[7] pH is a measure of how acidic or alkaline a water-based solution is. A pH of 7 means that the solution is neutral (neither acidic or alkaline), a pH of less than 7 means that it is acidic, whilst a pH above 7 means that it is alkaline.

5.3

Benefits of applying digestate to soil

The long-term benefits to soil of anaerobic digestate are less clear cut than those of compost; nevertheless, a summary of relevant publications highlighting key research findings have been included

5.3.1 Soil organic matter and structure

As anaerobic digestion is better suited as a process to treat putrescible (easily degradable) organic wastes compared with composting, this affects the types of organic compounds present in digestate. In addition, as there is little evidence of humification during the process and the fact that lignin-containing materials are generally not treated anaerobically, digestate therefore has low concentrations of humic substances compared with compost. This is therefore a result of both the nature of the treated feedstocks and the anaerobic digestion (AD) process itself.

It is thought that somewhere between 20-95% of the carbon in organic wastes is transformed into gaseous carbon compounds (mainly methane and carbon dioxide) during AD (Möller 2015). Spectroscopic analysis of digestate has shown that the stabilisation of digestate is due to the accumulation of stable carbon compounds during the process as the more labile compounds are degraded, rather than humification *per se* (Marcato *et al.* 2009).

Möller (2015) cites a few research papers where digestate has been shown to reduce soil bulk density, increase aggregate stability and increase moisture retention; however, he also notes that "an assessment on the long-term direct effects of digestate application on soil physical properties in comparison to the undigested feedstock is not available".

Research in the UK indicated that food waste- and manure-derived digestate applied at a number of sites over a three-year period was shown to increase soil compaction (measured by bulk density, shear strength and penetration resistance), although the authors were unable to identify why this happened (Bhogal *et al.* 2016).

Overall, it is thought that anaerobic digestate has a negligible effect on soil organic matter in the long term (Möller, 2015).

5.3.2 Soil biology

Increases in soil microbial activity have been measured following digestate application. Möller (2015) noted that "many reports indicate an enhanced soil microbial activity after field applications of digestates in comparison to inorganic fertilizers or untreated controls", which is thought to be due to nutrient supply. He concluded that the "main direct effects of anaerobic digestion on the field level are short-term effects on soil microbial activity and changes in the soil microbial community".

Although increases in soil microbial activity have been noted, Bhogal *et al.* (2016) reported a decrease in earthworm numbers following food waste-derived digestate application compared with the fertiliser control, which was attributed to ammonium-nitrogen levels.

5.3.3 Soil fertility

The significant benefit of applying digestate to soil is its high nutrient content (see for example: Fachverband Biogas, 2018 and WRAP 2019). Unlike compost, most of the plant nutrients (N, P and K) are present in mineral form, so they are readily available for crop uptake. Digestate is therefore best viewed as a biofertiliser.

Improvements in soil nutrient levels have been noted by numerous authors, including Möller (2015) and Bhogal *et al.* (2016).

Conclusion

This report summarises some of the physico-chemical properties of soil and outlines the important role it plays in providing a medium for humans to grow food. Notably, soil organic matter is an important reservoir of carbon, storing more than the atmosphere and terrestrial vegetation combined. However, this finite resource is under threat due to erosion, nutrient depletion and pollution, with one estimate suggesting that over the last 40 years about 30% of the world's cropland has become unproductive. Recently, the Food and Agriculture Organisation of the United Nations has suggested that about one third of soil globally is moderately to highly degraded; in a world of increasing population and changes in climate, this has the potential to undermine humans' ability to grow and harvest food crops sustainably.

Waste management and recycling of organic waste can contribute to the improvement of soils. As just under a billion tonnes of organic municipal soil waste are thought to be generated annually, this is a valuable resource, containing both carbon and plant nutrients. Recycling it into compost can help improve soil and slow its degradation, and thereby go some way towards meeting the United Nations Sustainable Development Goals 12 & 15.

According to existing technical expertise and scientific research, compost and anaerobic digestate cannot be considered as being equivalent in terms of their soil amending properties and fertilising effects; overall, anaerobic digestate has been shown to contain agronomically useful quantities of plant nutrients increasing crop yields and reducing the need for chemical fertilisers, although its beneficial effects on soil organic matter content and structure have not yet been demonstrated scientifically. It is therefore best viewed as an organic fertiliser, as it contains recycled phosphorus (a critical raw material) and nitrogen (circumventing the need to manufacture mineral N fertilisers through energy intensive industrial processes)[8].

Compost is best classified as an organic soil improver. It is generally lower in available plant nutrients than digestate but contains stable organic matter (humic substances) that contribute towards a soil's organic matter content. Numerous studies have shown that repeated compost application can increase soil aggregate stability and soil pore size, reduce compaction and increase water holding capacity. Applying compost to soil has also shown that it can increase soil microbial biomass and microbial activity, as well as build up a nutrient store.

The main value of compost is its capacity to sequester carbon in soil, with studies summarised in this report suggesting that over a period of between 4-12 years in the region of 11% - 45% of the organic carbon applied to soil as compost remained as soil organic carbon.

As the World Bank has estimated that about a third of the world's municipal solid waste is not managed in an 'environmentally safe manner', the effective collection and recycling of organic waste can have a win-win outcome. The avoidance of vermin attraction and the generation of malodours and methane, as well as the improvement of agricultural soil has the potential to significantly improve lives, contribute towards increased food security, combat desertification, and help reduce atmospheric carbon dioxide levels.

The challenge for waste planners and waste managers is therefore to source and collect clean, contaminant free organic wastes, then recycle them into quality compost.

The implications for soil organic matter content are therefore potentially significant. The next report in this series will provide estimates of the potential theoretical benefits to soil that can be achieved globally and in a number of different countries, each having different soil types and climatic conditions.

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[8] The significant role of AD in producing biogas, a renewable, carbon neutral fuel, has not been considered in - and was out of the scope of - this document and should be taken into consideration when making a more general comparison between composting and anaerobic digestion of organic waste

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Dr Jane Gilbert

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Dr Jane Gilbert is a chartered environmentalist and waste management professional and has been involved in the organics recycling sector for over twenty years.

She is the former chief executive of the UK Composting Association, co-founder of the European Compost Network and vice chair of the International Solid Waste Association's Biological Treatment Working Group.

Jane originally trained as a microbiologist (BSc Hons), has a doctorate (PhD) in biochemistry and a Masters in Business Administration (MBA). She trades as Carbon Clarity, providing consultancy, training and writing services. Jane has authored a number of technical composting books and has presented at conferences in North America, Europe, Africa and Asia. She runs Carbon Clarity Press, specialising in publishing resources to support sustainable living.

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Chair of the ISWA Working Group on Biological Treatment of Waste, managing Altereko sas consulting, senior Expert at CIC - Italian Composting and Biogas Association.

He has 20 years of experience in planning MSW management, designing collection schemes by minimizing residual waste, assessing recycling facilities (focus on composting), planning communication initiatives, chairing multi-linguistic, multi-tasking working groups or projects. With a specific engagement for MSW solutions in cities, he supported the City of Milan (Italy) in setting up the recycling scheme for food waste in 2012 and worked with the Mega-City of Sao Paulo (Brazil) for the strategy to divert organic waste from landfilling towards recycling in cooperation with ABRELPE and UN-CCAC.

Aditi Ramola

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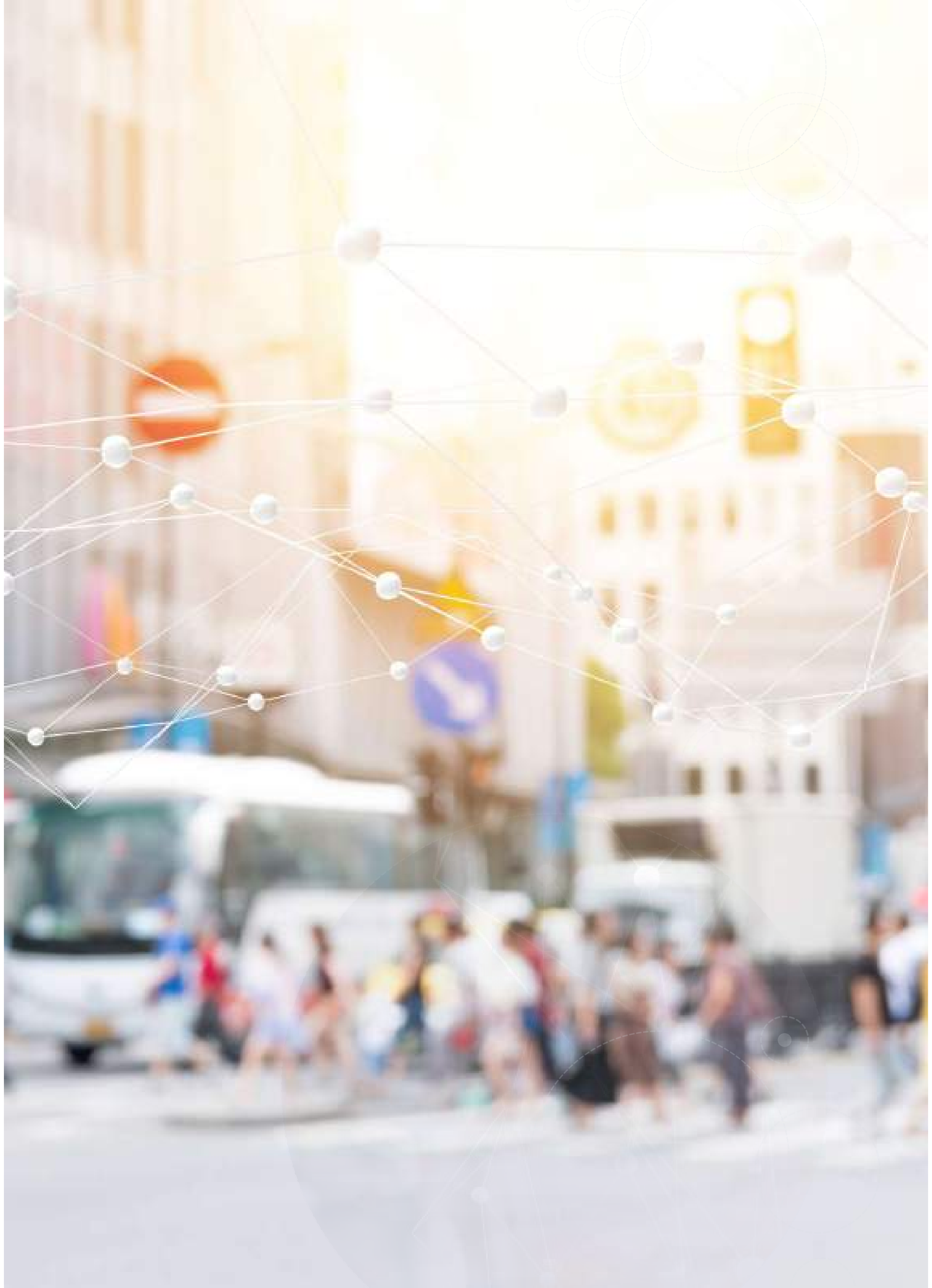
Aditi is currently the Technical Director at the International Solid Waste Association (ISWA) where she manages international projects and partnerships with the UN, provides assistance to ISWA's Working Groups and helps develop innovative projects globally to further strengthen cooperation with ISWA's partners and international organizations.

Her skills are particularly focused on solid waste management and environmental issues. Aditi holds a master's in Environmental Technology and International Affairs from the Vienna University of Technology. She has several years of experience in the private sector including at Caterpillar Inc. before joining the United Nations Industrial Development Organization (UNIDO) in the Climate Policy and Networks unit. Aditi was the Chair of the ISWA Young Professionals Group (YPG) for 2019. She is also passionate about science education and currently leads the ISWA YPGs initiative on Education.



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