Biology of compost

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Introduction **2**
Definition of composting (process) and of compost (product) **2**
Scope of this chapter 2
The substrates **2**
Cellulose 3
Lignin 3
Hemicelluloses 3
Chitin 3
Murein 3
Other compounds like collagen or keratin 3
Supplements 3
The organisms and process phases **4**
The commonly recognized composting at farm- and industrial scale 4
Initiation phase 4
High temperature phase (35–65 °C) 5
Cooling phase 5
Maturation phase 5
Curing phase 5
When is compost mature? 5
Vermicomposting 5
Black soldier fly composting 6
The products **7**
Added value, carbon and nutrients 7
Method of quality assessment 8
Effects on soils **8**
Microbial diversity, macro and micropores, aggregates and structural stability 9
Climate related issues **9**
Conclusion **10**
References **10**

Glossary

Frass In natural environments, frass describes the excreta of insects. From the perspective of insect farming, however, frass is defined and marketed as an inhomogeneous mixture of feeding substrate residues, insect feces and body parts, exuviae, and dead insects that is collected after separating the harvest-ready insects at the end of the rearing process. Frass application introduces beneficial microorganisms to the soil and its chitin fraction is considered a resistance-promoting agent for plants.

Key points

- Substrates for composting processes
- Microbial vs. faunal-driven composting
- Effects of composts on soils, their microbiota and plants
- Composts for mitigation of climate warming

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Introduction

In the context of global warming and a renewed debate on fossil energy, sustainable agricultural, horticultural and silvicultural approaches are receiving more attention. Indeed, the recycling of carbon (C) and nutrients to soil may alleviate the extensive use of fossil resources. Apart from rendering the soil as a sink for C, we should keep in mind that $\sim$2% of the global anthropogenic energy use is attributed to the Haber-Bosch process to collect nitrogen from the atmosphere. With increasing prices for fertilizers, organic amendments such as manures or composts are becoming more attractive as sources of nutrients and organic matter.

Soil degradation as a result of extensive agricultural or horticultural use, combined with poor management, remains a major concern and often related to the loss of organic matter and a low level of nutrient availability. Composts may either be incorporated into the soil or used as mulch. Both approaches have advantages and disadvantages. Often, the effects are best detected in the vicinity of the applied material, which is of practical interest as roots grow toward such hotspots where they take immediate advantage of the nutrients released from the composts (Duong et al., 2013).

Definition of composting (process) and of compost (product)

Etymologically, composting (from Latin, *compositum,* mixture) refers to a biodegradation process, not of a single material but of a mixture of substrates. In addition, the process is carried out by a mixed community of organisms, be they only microorganisms, or microorganisms and fauna. The microbial conversion of pure substrates would be called fermentation or bio-oxidation, but not composting. Composting is commonly carried out on the basis of solid substrates (also rich in lignocelluloses), and is generally understood as an aerobic process. The exothermic process generates energy in the form of heat, resulting in an increase in temperature. A spontaneous process characteristically goes through five phases, an initial mesophilic phase, followed by a thermophilic and subsequent cooling (second mesophilic) phase, maturation and a terminal curing phase. During composting a temporary release of phytotoxins (intermediate metabolites, ammonia, etc.) is typical, while in the terminal phase this phytotoxicity is overcome and the end product benefits plant growth. The composting process results in CO_2, water, minerals and stabilized organic matter (often referred to as 'humic' material, a concept that has, however, been challenged by Lehman and Kleber, 2015). In brief, composting is based on a mixture of substrates and degrading organisms, particularly microorganisms, and is characterized by a constantly changing physico-chemical environment, including nutrient availability, pH, temperature and composition of intermediates (Insam and De Bertoldi, 2007; Insam et al., 2002). Although some authors term anaerobic treatment (in particular biomethanization) anaerobic composting, this process is explicitly not covered in the present chapter. The end product of anaerobic processes is called digestate, and does in many respects have different effects on soils than do composts (Gómez-Brandón et al., 2016). Post treatment of digestates by composting, however, may well be used to stabilize the material, again resulting in a product termed compost.

The main product of the process is called compost, which can be defined as stabilized and sanitized, compatible with and beneficial to plant growth. The conversion of waste organic material into compost is carried out for three main reasons, (i) to overcome the phytotoxicity of fresh, unstabilized organic material, (ii) to reduce the presence of pathogens (viruses, bacteria, fungi, parasites pathogenic to humans, animals and plants) to a level that does not pose a further health risk, and (iii) to produce an organic soil amendment that serves the purpose of nutrient addition and physico-chemical conditioning. This way biomass in the form of organic waste and crop residues is recycled.

Scope of this chapter

There is a plethora of different methods of composting, ranging in size from miniature backyard to huge industrial operations, and involving many different substrates from agricultural residues to kitchen waste and municipal sewage sludges. There are rapid processes, and others that take more time; there are pure microbiologically driven processes and ones that exploit the activities of mesofauna. In this chapter there will be a focus on medium- to large-scale, farm-scale and commercial composting, as well as on vermicomposting and organic waste treatment by the black soldier fly.

The substrates

Basic for any composting process is the availability of degradable organic matter which is usually of plant origin, but my also stem from faunal tissue or microbial cells. The basic materials are presented below, each with its own properties for the process. Owing to the biochemical composition of the substrate material, the composting process runs differently, and also the resulting compost quality may be different. Basic substrates range from manure or other agricultural or agro-industrial residues, to domestic organic waste from source-separated collection and slurries from wastewater treatment plants. Also, mixtures of such wastes are often used, including lignocellulosic materials (bush- and tree cuttings), which serve as bulking agents, or digestates from biomethanization plants.

Cellulose

Cellulose as the most abundant component of plants is found in many types of organic waste. Waste rich in structural elements (such as wastes from the wood industry and straw from agriculture) has the highest cellulose content, while domestic organic (kitchen) waste contains less, and wastes derived from microbial or animal sources contain no cellulosic material. Cellulose molecules are chains of β-1,4-glycosidic bonded glucose with a polymerization degree of up to 40,000. Enzymatic degradation is brought about by the activity of three enzymes, (i) Endo-β-1,4-glucanase, (ii) *exo-* β -1,4-glucanase and (iii) β –glucosidase, the resulting glucose is taken up by the microorganisms and used for energy and as base molecules in anabolic processes.

Many fungi and bacteria are involved in the breakdown of cellulose. The catalytic effect (mechanical destruction) of micro- and mesofauna may be an important contributing factor. Fungi are generally more important than bacteria in breaking down cellulose, especially when cellulose is encrusted in lignin (e.g., in straw or wood). Because cellulose is rich in C but lacks N or other essential elements, the hyphal structure of fungi has a competitive advantage as the hydraulic force of fungal hyphae can break up lignocellulosic material. *Chaetomium*, *Fusarium* and *Aspergillus* are important fungi to mention in this context; cellulose-degrading bacteria mainly belong to the Myxomycetes or related classification groups (*Cytophaga*, *Polyangium*, *Sorangium*). *Pseudomonas* and related genera are also known to degrade cellulose, as are Actinobacteria.

Lignin

Lignin is a most recalcitrant structural component of plants, making up 2–30% of their biomass. It is composed of few monomeric units (phenylpropane derivatives, mainly coniferyl and sinapyl alcohol) but, due to the extraordinary variety of chemical bonds involved, its degradation is complex and yields little energy. Very often, the degradation of lignin is of a co-metabolic nature, primarily accomplished by fungi, in particular white-rot fungi such as *Trametes versicolor* or *Stereum hirsutum*. They break down the lignin, leaving behind cellulose parts that are light in color. Some fungi, such as *Pleurotus ostreatus*, degrade both cellulose and lignin.

Hemicelluloses

Among the hemicelluloses, xylan is most important, found in straw, bagasse and wood. It contains pentose sugars, such as arabinose and xylose, as well as hexoses, including galactose, glucose and mannose with a degree of polymerization of 30–100. Pectin, made up from unbranched chains of polygalacturonic acid, is degraded by pectinase, commonly produced by fungi and bacteria. Starch contains amylose (20%) and amylopectin. The former are unbranched helical (due to 1,4-position β-glycosidic bonding) chains of D-glucose, while the latter, containing phosphate residues and Ca and Mg ions, is also branched at the 1,6-position. Two types of enzymatic degradation are important, phosphorolysis (releasing glucose-1-phosphate) and hydrolysis (α-amylase cleaving the α-1,4-bonds within the molecule).

Chitin

Cellulose and chitin are chemically very similar. In chitin, glucose is replaced by N-acetylglucosamine, which makes a difference for degraders since chitin contains approximately 7% N (C:N-ratio = 7). Many fungi and bacteria use chitin both as an N and C source. Chitin is degraded to *N*-acetylglucosamine, which is resorbed, transformed to fructose-6-P and channeled into the carbohydrate metabolism. Chitin is an important structural compound in fungal cell walls, makes up the exoskeleton of crustaceans and insects, making it an important waste product from pharmaceutical and shellfish industries.

Murein

Murein, consisting of unbranched chains of N-acetylglucosamine and N-acetylmuramic acid bound to variable amino acids. Murein is the main cell wall component of most bacteria, and thus only a minor component of most waste streams. It may, however, be an important component of wastes derived from the pharmaceutical industry, and in wastewater slurries.

Other compounds like collagen or keratin

Proteinaceous compounds stemming from animal wastes serve as slow-release nitrogen sources and contribute to the value of the resulting compost. Often, they are contained in the digestates of biogas plants that are using slaughterhouse wastes.

Supplements

The supplementation of composts with by-products, such as biomass ash (Kuba et al., 2008; Bougnom et al., 2010) and biochar (Agegnehu et al., 2017) serves two purposes, the reduction of waste and the improvement of the product. Biomass ashes provide major nutrients like phosphorus (P), a multitude of micronutrients and also serve as a lime replacement, while biochar provides exchange sites, micro-niches for microorganisms and improves the physical structure of composts. There is consensus that the mixing of composting substrates and supplements prior to the composting process adds additional benefit compared with mixing prior to soil amendment. Other supplements, such as rock dust, are known for similarly positive effects, mainly through providing nutrients and facilitating the formation of mineral-organic complexes (aggregates). It has been reported that not only the soil microbiome is changed, but the effects extend as far as improving the vitamin C content in apples (Li et al., 2021).

The organisms and process phases

The commonly recognized composting at farm- and industrial scale

In contrast to small-scale backyard processes, larger scale operations do usually not allow for micro- or mesofauna driven processes, but rely on purely microbially driven turnover. This is because of the speed of the process (6–12 weeks) and the need for mechanical disturbance by either periodic or continuous turning. Such operations mostly rely on a well-designed process regulation based on measurements of carbon dioxide or oxygen content, temperature, pH and moisture. Also, pretreatment of the substrate material, including cutting, milling and sieving plays an important role, as does active or passive aeration, and moisture control. Five phases are typically involved (Fig. 1).

Initiation phase

In this first phase (also called starting phase or first mesophilic phase), easily degradable compounds like sugars and proteins are abundant and are initially degraded by mesophilic or thermotolerant (20–35 °C) fungi and bacteria, including actinobacteria. Ryckeboer et al. (2003) found few mesophilic fungi in source-separated household waste, but numerous thermophilic fungi and bacteria. Initially, food wastes containing vegetable residues often have a low pH (4.5–5.0) that stimulates the proliferation of fungi and yeasts. Ammonification causes an increase in pH, favorable for bacteria that subsequently colonize the substrate. Wastes that are rich in lignocellulosic matter show a different composition, still with a high microbial diversity but having a bias toward fungi.

However, due to the more rapid growth of bacteria, and a metabolism-driven temperature rise, fungi and yeasts are soon outcompeted. The high surface:volume ratio of bacteria allows a rapid transfer of soluble substrates into the cells. Bacteria are taxonomically and nutritionally the most diverse group, equipped with a broad range of enzymes to degrade a variety of organic materials. Also, the bacterial generation time is much shorter than those of fungi, which gives them a competitive advantage. Actinobacteria tend to grow slower than many other bacteria and are ineffective competitors when nutrient levels are high (Beffa et al., 1996); they thrive, however, as soon as the most easily degradable substrates are exploited. Due to their ability to produce various antibiotic substances, actinobacteria (e.g., streptomycetes) are most important for hygienization, inhibiting the growth of

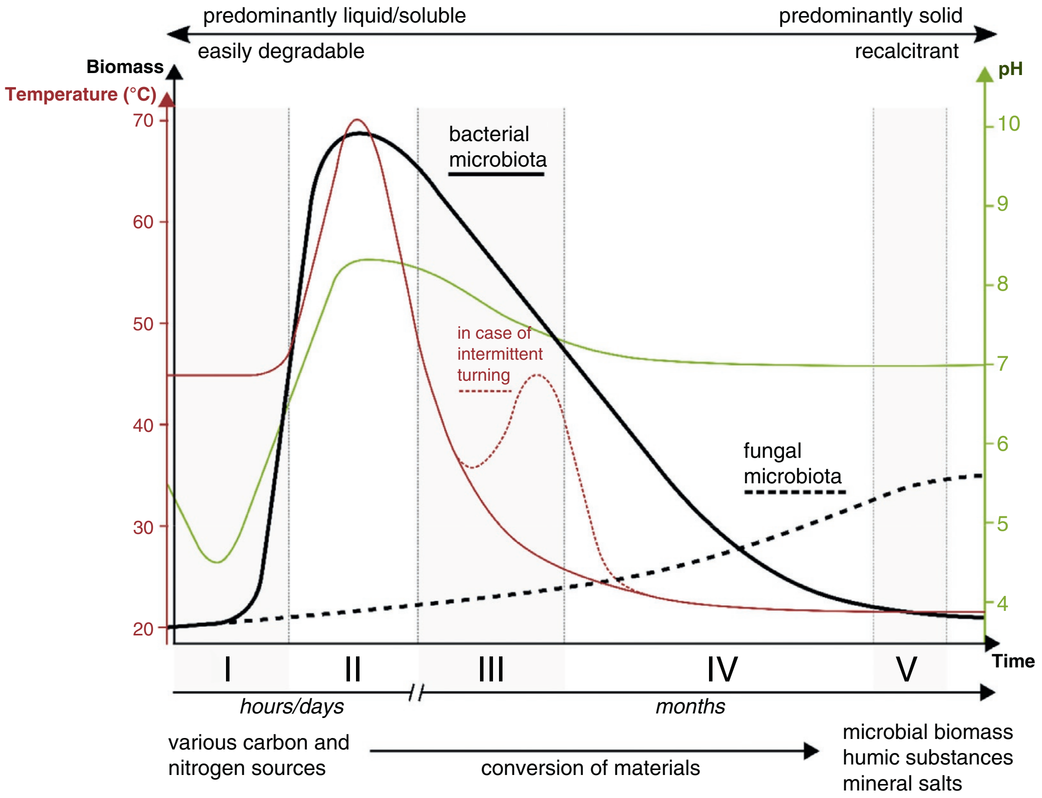

Fig. 1 Biomass, temperature and pH as they typically evolve in a composting process. The graph also shows dominant microbiota at two stages, as well as main material conversions.

many human, animal and plant pathogens. If mechanical influences (like turning) are very limited, fauna, such as compost worms, mites, millipedes, and mesofauna develop, which mainly act as catalysts through their ability to physically disrupt substrates. Important regulators of microbial activities are protists, as well as viruses, including bacterial and fungal phages.

High temperature phase (35–65 °C)

When process temperature rises, thermophilic and thermotolerant organisms get a competitive advantage and gradually replace the mesophilic biota. Previously flourishing mesophiles die off and are eventually degraded by the succeeding thermophiles. Overall bacterial species diversity falls significantly during the thermophilic phase. The number and diversity of thermophilic actinobacteria increases, however, particularly at temperatures of 45–55 °C (Amner et al., 1988; Beffa et al., 1996). The decomposition runs fast and accelerates temperature increases up to about 62 °C. The rise in temperature is another reason why bacteria outcompete fungi. Temperatures exceeding 60 °C inhibit fungal growth, but they may survive as spores. Yeasts disappear during the thermophilic phase, but when the temperature cools down to 54 °C, they reappear (Ryckeboer et al., 2003). Endospore-forming bacteria, such as *Bacillus stearothermophilus*, are often considered typical for composting processes. They are very active at temperatures higher than 50 °C or even 60 °C (Ryckeboer et al., 2003). Non-spore forming bacteria such as *Hydrogenobacter* spp. and *Thermus* spp. are among the dominant ones in the hottest phase of the process, active at temperatures >70 °C and up to 82 °C.

Thermal inactivation of pathogens is required to obtain safe products, both in terms of phytohygiene and human diseases. The higher the temperature, the more efficient will be the destruction of pathogens (Ryckeboer et al., 2003) albeit temperatures exceeding 80 °C may trigger the Maillard reaction, leading to undesired odor and microbial inhibition. Millner et al. (1987) showed that pathogen suppression was more efficient in composts produced at 55 °C than at 70 °C. Additionally, regrowth of mesophilic populations may be delayed if too high temperatures are maintained for a long time and if this temperature is reached throughout the composting material, calling for appropriate reinoculation schemes.

Cooling phase

As soon as the easily available substrates are exhausted, the temperature starts to decrease. Mesophilic organisms recolonize the substrate, originating from surviving spores, through spread from protected microniches, or airborne inoculation, or as organisms attached to turning or sieving machinery. In this medium-temperature phase the available substrates are much different to those in the first low temperature phase. They are largely dominated by secondary degradation products, and recalcitrant polymers, such as starch, cellulose or lignin, and also thermally inactivated microbial cells.

Maturation phase

Lignin, cellulose and other recalcitrant compounds are decomposed by specialized microbiota equipped with ligninases, peroxidases and cellulases. The maturation phase is important for the build-up of humic acids that are either generated from aromatic compounds derived from the lignin, or are synthesized de novo. The humic matter is among the most valuable components of composts. During maturation, fungi are starting to outcompete bacteria, of which *Arthrobacter* form a numerically important fraction. Species diversity seems to be correlated with stability of the end product (Beffa et al., 1996). After incorporation into soils, immature composts may induce enhanced microbial activity and cause oxygen deficiency and a variety of phytotoxicity problems to plant roots.

Curing phase

Some researchers refer to a post-maturation, so-called, curing phase. In this phase, it is hardly possible to diagnose changes in physical or chemical compost quality. However, changes in the microbiota may still occur to the benefit to the product (Danon et al., 2008) but also to its disadvantage, for example, because of decreased plant disease suppressiveness (Franke-Whittle et al., 2019).

When is compost mature?

Classical maturity tests are discussed in detail by Itävaara et al. (2002) and Insam and de Bertoldi (2007). Benefits of compost application, such as suppression of diseases caused by soilborne plant pathogens, have been reported in agricultural and horticultural crops. Composts in their early stages often exert phytotoxic effects that may be associated with ion concentrations, excessive availability of heavy metals, toxic organic compounds or an adverse phytopathogenic microbiota. Phytotoxicity is defined as a delay of seed germination, inhibition of plant growth through, e.g., phytotoxins. During compost maturation these effects are commonly alleviated, rendering the composts compatible with plants and plant roots. Compost maturity tests based on phytotoxicity is a well-established methodology, worldwide (Bernal et al., 2017), as are tests based on ammonia or carbon dioxide release, or self-heating tests in Dewar flasks (Rottegrad test; Table 1) (Itävaara et al., 2002; Changa et al., 2003).

Vermicomposting

In general, small-scale composting favors faunal-driven composting, in contrast to large-scale operations that favor microbially dominated processes. Only in special cases, like vermicomposting or black-soldier-fly (BSF) driven operations, does large scale also enable a faunal-driven process.

Table 1 Rottegrad, definition of process conditions.

Rottegrad	*T_{max} in °C*	*Product*
I	>60	Fresh compost
II	50–60	
III	40–50	
IV	30–40	Mature compost
V	<30	

Unlike composting, vermicomposting does not include a thermophilic phase and relies on the synergistic actions of earthworms and microorganisms to accomplish the breakdown of the organic matter. Earthworms have been classified, on the basis of their feeding and burrowing strategies, into three ecological categories: epigeic, anecic and endogeic. In particular, five epigeic earthworm species have been extensively used in vermicomposting facilities known as *Eisenia andrei* (Savigny), *Eisenia fetida* (Bouché), *Dendrobaena veneta* (Savigny) and, to a lesser extent the tropical species *Perionyx excavatus* (Perrier) and *Eudrilus eugeniae* (Kinberg). These earthworm species live in the soil organic horizon, in or near the surface litter, and mainly feed on fresh organic matter contained in forest litter, litter mounds and herbivore dung, as well as in man-made environments such as manure heaps. All display a natural ability to colonize organic wastes and are characterized by short life cycles, high reproductive rates and a high rate of consumption, digestion and assimilation of OM.

Vermicomposting systems sustain a complex food web that results in the recycling of organic matter (OM) and the release of nutrients (Domínguez et al., 2010). However, more than a century passed before vermicomposting was considered a viable technology, despite the important role of earthworms in the decomposition of dead plants and nutrient cycling. During vermicomposting, epigeic earthworms and microorganisms intensively interact accelerating the stabilization of OM and greatly modifying its physical and biochemical properties. Although microbes are responsible for the biochemical decomposition of the OM via the production of extracellular enzymes, earthworms are key players in the process through their effects on microbial communities. They may influence microbial decomposer activity by grazing directly on microorganisms, or by increasing the surface area available for microbial attack after the comminution of organic matter. Earthworm activity favors the aeration and fragmentation of OM, thereby enhancing its turnover and increasing the rate of decomposition. They can also affect other fauna directly through the ingestion of microfaunal groups (protozoa and nematodes) that are present in the detritus consumed, or indirectly by modifying the availability of resources for these groups.

In the short-term, the earthworm gut-associated processes, that is the ingestion, digestion and assimilation of OM and then casting, are major drivers of the vermicomposting process. Earthworms excrete large amounts of egested materials known as casts that result in an inoculum of nutrients and microorganisms into the environment. The contact between these materials and the raw substrate has been found to alter the nutrient dynamics and the rate of OM decomposition, similar to that when earthworms are present. The changes occurring during these initial stages of vermicomposting largely determine the properties of the final product and its potential usefulness as an organic amendment. A period of aging is also necessary to obtain a mature, phytotoxic-free vermicompost for its proper use to promote plant growth and suppress plant diseases. The duration of the maturation phase is not constant and may vary depending on how efficiently the initial phase of vermicomposting is performed.

Vermicompost is considered a nutrient-rich, peat-like material characterized by a large porosity and water holding capacity, but a small C:N ratio. Beneficial effects of vermicompost have been documented for a wide variety of agronomic and horticultural crops, when used as an amendment for soil or plant growth media. These positive effects have also been reported for extracts and teas made from vermicompost (Gómez-Brandón, 2015), even though they do not impart the same physical properties as solid vermicompost. Various factors such as an improved availability of air and water, the presence of plant-growth regulating substances, and the mitigation or suppression of plant diseases have been proposed as plausible, albeit not exclusive, mechanisms by which such improvement is achieved. There is also evidence of microbial-based mechanisms that may explain the positive influence of vermicompost on soil and plants (Gómez-Brandón et al., 2020). Compared with the initial substrate, the resulting vermicomposts exhibited a greater functional diversity and higher abundance of putative genes related to specific metabolic processes, i.e., biosynthesis of antibiotics or plant hormone synthesis, potentially beneficial for plant growth and development.

Black soldier fly composting

Insects are increasingly gaining scientific and economic interest as agents for organic waste management. In terms of fertilizer production, converting organic waste into a stable soil amendment follows a similar principle as vermicomposting. In contrast to earthworms, however, industrially used insects are not primarily seen as producers of compost but rather as bioreactors capable of transforming low-value substrates into a source of value-added products that include protein, fat, chitin, and they also yield a by-product with fertilizing properties. Most of these products are directly derived from mechanically or chemically processing the raw insect biomass. The residue fraction, however, accumulates as the major by-product of the rearing process and has recently been defined by the European Commission as a mixture of digested and undigested substrate wastes, shed skins, and also to the smaller portion of dead insects. The beneficial effect of insect droppings on soil nutrient dynamics and their effect on soil respiration was described in detail in the past. With the emergence of insect farming, these benefits are now being exploited on an industrial scale. Thus, the term "frass," originally used to describe these insect droppings in natural environments, has been adopted to include the rearing residues and is nowadays commonly used to describe this complex insect-derived compost.

Among the few species approved for commercial insect farming in the EU, the black soldier fly (*Hermetia illucens* Linnaeus, Diptera: Stratiomyidae) is considered the most promising contender to drive the worldwide expansion of this emerging industry. Also, in natural environments, the progressing globalization and increasing average temperature contribute to the cosmopolitanism of this subtropical fly, thereby driving its dispersion across all continents except Antarctica. In recent years, efforts were mainly directed toward determining organic waste streams from industries that are suitable for bioconversion by black soldier fly larvae (BSFL). Primarily agro-industrial by-products (e.g., wheat bran, spent grains) or fruit and vegetable wastes find current application in Western countries. Due to the novelty of large-scale insect farming, legal restrictions, and immature research on the safety of insect-derived products limit the use of a broader variety of substrates that would otherwise also include animal manure or food wastes (Liu et al., 2022).

In contrast to compost, which typically matures from an inconsistent and diverse mixture of organic wastes into a largely homogenous product with comparable properties, most of the frass physicochemical properties and nutrient content vary markedly according to the rearing substrates employed (Klammsteiner et al., 2020). Therefore, the blend of organic compounds making up the rearing substrate must be well described and available in consistent quality to ensure efficient production, as the ratio of its ingredients will consequently determine the quality and fertilizing properties of the frass. The conversion of substrate into insect biomass results in a reduced N and P content in the residues compared to the original material, though the bioavailability of the nutrients is increased through insect digestion. Commercial frass from BSFL shows on average an N:P_2O_5:K_2O ratio of 1:0.9:1.1 with a relatively high C:N ratio of 14.7 (Gärttling and Schulz, 2022). In comparison with other insect species, BSFL frass contains significantly larger concentrations of N ($<130\%$) and K ($<190\%$) (Beesigamukama et al., 2022). Although BSFL can thrive in a wide range of pH levels, the pH in frass is among the few parameters that show little variation across production systems and starting substrates (Gärttling and Schulz, 2022). Even frass from initially acidic substrates (pH 4) becomes alkaline (up to pH 9) during the process, approximating the high pH in the larvae's posterior gut (Bonelli et al., 2019).

Frass from BSFL also induces a higher germination rate and germination index than rearing residues from other industrialized insect species (Beesigamukama et al., 2022). This might be favored by the presence of plant growth-promoting rhizobacteria and other beneficial microbes (Barragán-Fonseca et al., 2022). The frass itself has been shown to have inhibitory effects on multiple plant pathogens and shows insecticidal properties (Vickerson et al., 2015). This effect is supported by the innate microbiota of the frass, in which the microbial community becomes more similar to the one inhabiting the BSFL guts as more and more of the substrate is digested (Gold et al., 2020). Especially bacteria (Gammaproteobacteria and Bacilli) and fungi (Ascomycota) present in the frass support the larvae in degrading the organic matter by driving aerobic fermentation (Barragán-Fonseca et al., 2022). This process could be further improved by inoculating the substrate with specific species such as *Bacillus subtilis*, as supplementing these bacteria is capable of enhancing frass maturation, seed germination, and enzymatic activity (Xiao et al., 2018). Unlike compost and vermicompost, frass also contains substantial amounts of chitin from insect skins and exuviae which not only serve as source of plant nutrients, but also enhance plant defense mechanisms by positively stimulating the soil microbiota (Barragán-Fonseca et al., 2022). While the inactivation of pathogenic microorganisms and phytotoxins in compost relies on one or more thermophilic phases, pathogens in BSFL frass are inhibited by antimicrobial peptides excreted by the larvae (Klammsteiner et al., 2020). To ensure the biological safety of frass, a first legal standard that requires a 70 °C heat treatment as post-processing measure has been recently introduced by the EU commission. To achieve this, frass could either be dried or composted prior to commercialization or soil application. However, frass that was treated via aerated composting was shown to cause 20% higher greenhouse gas emissions compared to its direct use, but could offer a feasible way to enhance nutrient availability and biosafety (Song et al., 2021). Any such post-treatment of frass, however, counteracts the very positive effects of untreated frass, as explained above, and a re-evaluation of the respective EU legislation.

Several studies ranging from pot to field scale indicate that frass application can achieve similar yields as common nutrient application regimes, however, with less negative consequences for the environment than, for example, manure (Liu et al., 2022). Current environmental challenges associated with the use of manure or inorganic NPK fertilizers such as increased leaching or eutrophication could be alleviated by supplementing or partially substituting them with frass. At field-scale, a combined use has shown to enhance crop yields and reduce losses from plant diseases due to the promotion of several plant defense mechanisms (Barragán-Fonseca et al., 2022). With further expansion of the insect farming sector and additional efforts for standardizing rearing substrates and rearing systems, the high variation in macro- and micronutrients in frass is expected to decrease. N and P can be recaptured from the food chain by integrating these residues as biofertilizers in agriculture, thereby closing nutrient and material cycles according to the principles of the circular economy.

The products

Added value, carbon and nutrients

Beyond the delivery of nutrients, most of them in a slow-release-form, composts confer numerous additional benefits to soil that range from increased soil C stocks and increased water holding capacity to plant disease suppressiveness. All the effects of composts, however, are determined by the available input materials, and the prevailing process conditions. Thus, the above mentioned three levels of control, quality of input materials, process and end product, are required for reproducible end products with their distinct effects on soils and plants.

Method of quality assessment

Compost quality is defined both by the quality of the input material and the resulting end product, as well as by the process conditions. The composting process is designed to secure an 'end-of-waste status' for the substrates. Input material, ranging from lignocellulosic wastes to wastes with a higher proportion of proteins, sugars or other short-chained carbohydrates (see above), have inherent elementary properties. Apart from nutrients and C, they these also may contain heavy metals and xenobiotics and human, animal and plant pathogens. In particular, maximum allowed heavy metal contents are regulated, both in the substate sources and in the end product in case of a destined use in agriculture, horticulture or forestry. The legal conditions, however, vary from country to country. For xenobiotics and pathogens, the composting process is critical for their elimination. Thus, process conditions are often strictly defined, such as the process temperatures that must be reached.

Effects on soils

An advantage of compost over mineral fertilizers is its ability to slowly release nutrients into its environment, often in line with plant needs, which increase as spring temperatures rise. As soon as the soil warms up and the plants start to grow, the activity of the microorganisms that release the nutrients also increases. Slow-release mineral fertilizers were thus developed to give mineral fertilizers this beneficial property, inherent to organic fertilizers. A disadvantage of compost is that the entire nutrient content is not released in the first year of use, but only fractions of it, which complicates the annual calculation of requirements (Insam and Merschak, 1997).

In addition to the nutrient content, compost has other properties that makes it valuable: compost improves the condition of the soil. It has a favorable influence on soil structure and soil texture (Fig. 2). As a result, nutrients, water and air are better retained, which ultimately increases yields in horticulture and agriculture.

In good soil, sand, clay, and loam mix together into aggregates that allow aeration and drainage. Ideally, the earth is granular and crumbly; a large sand content makes the soil too coarse-grained but with a high clay content it may be too compact. Too much clay can promote waterlogging and the soil becomes impermeable to air. Compost creates pores of various sizes that fill with air and water, rendering them available for microbial metabolism and microbe proliferation, ultimately offering an ideal substrate for plants. On the other hand, if the soil is too sandy, the water drains away too quickly. In this case, the addition of compost contributes to the formation of larger granules that are surrounded by a film of water on their surface. The addition of compost compensates for a high proportion of sand or clay and promotes the formation of aggregates (clay-humus complexes). Between these aggregates, large and often air-filled pores are maintained that allow diffusion of air (oxygen) into the soil and the outward diffusion of CO_2. Compost amendment has also shown to change the pattern of emitted volatile organic compounds (VOC) (Seewald et al., 2010).

The greater the proportion of decomposed organic matter in its various stages protected from further decomposition, the larger is the water holding capacity of the soil, which counteracts the risk of desiccation, since 100 kg of humus are able to store 195 kg of water. The storage of water can counter the leaching of valuable minerals in drainage. If a soil is subject to chemical fertilizers over a long time, it loses its structural properties. Remedial tillage, fertilizers and irrigation must be used more. Maintaining a healthy soil structure is also a protection against erosion. Good soil structure also ensures optimal ventilation; oxygen promotes the uptake of potassium by plants and enables the synthesis of SO_2, CO_2 and the conversion of ammonia to nitrate.

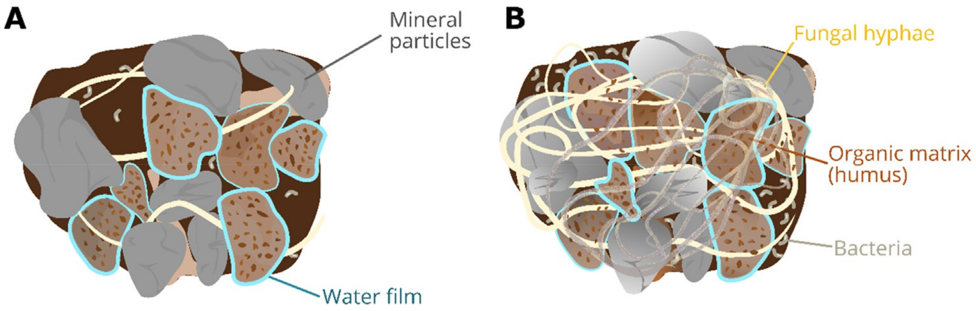

Fig. 2 Visualization of the effects of compost addition on the physical and microbiological properties of soil aggregates. Left: depleted soil with poorly developed pore structure and microbial diversity, right: soil that has received compost: formation of stable soil aggregates hosting pores of various sizes and an enhanced microbial diversity.

Another positive influence of compost is its ability to neutralize toxins. Organic matter has a large capacity to bind heavy metals. Insoluble, stable complexes are formed that cannot be absorbed by the plant and are thus withdrawn from the food chain. Gómez-Brandón (2015), Kranz et al. (2020), and Ryals et al. (2014) provide the basis for an overview of the effects of compost (including vermicompost and compost teas) on plant growth and soil fertility, which may be summarized as follows:

- Enhanced nutrient retention
- Carbon sequestration
- Reduction of bulk density
- Enhanced water holding capacity, infiltration, hydraulic conductivity and plant available water
- Improved aeration (beneficial for both microorganisms and plant roots)
- Increased microbial diversity
- Increased plant disease suppression
- Enhanced resilience toward disturbances (high or low temperatures, drought)
- Decreased susceptibility to water and wind erosion
- Immobilization of cations, including heavy metals, rendering them unavailable to plants

The difference between inorganic and organic fertilizers on the one hand and compost on the other, is the dynamics of nutrient release. This may, depending on the composition on the fertilizers, be uncontrolled and fast, but it may also be retarded owing to specific formulations. The nutrient release dynamics of composts is mostly not as well defined, and depends a lot on the C:N:P-ratio and on the maturity of the compost. However, it accords quite well with plant demand because the nutrient release depends on the activities of microbes and microfauna, which are regulated by temperature and moisture availability, as is plant growth and nutrient uptake. The fertilizer effect of composts is often disputed, and indeed, it has been shown that a combination of slow-release compost with fast release fertilizer may be a way to combine the benefits of both (Ros et al., 2006). The high-nutrient component does not necessarily need to be mineral fertilizer, but could also be a fast-release organic fertilizer, such as manure. The choice of mineral or organic forms of nutrients could be based on whether the soil was dominated by bacterial or fungal biomass as the result of previous fertilizer strategies (Semenov et al., 2022). For nutrient balancing, agronomists assume that the nutrient release of compost is not greater than 20% of its content in the first, and even less in the subsequent years. Thus, the change of management practice from mineral to organic nutrient application, with the sole use of compost, may result in an initial nutrient deficit that is alleviated through repeated additions of compost in the following years.

Microbial diversity, macro and micropores, aggregates and structural stability

Biodiversity is an issue that is attracting increasing attention and so is diversity of soil microorganisms, a subject linked to resilience and resistance toward disturbances (Lynch and St. Clair, 2004). Abundant research has shown that the use of composts contributes to the microbial diversity in soils (Ros et al., 2006; Kurzemann et al., 2020). Microbial diversity benefits soils in two major ways: firstly, by safeguarding a steady nutrient supply through decomposition processes that cope with changing environmental conditions and, secondly, by supplying a microbiota that is disease suppressive. This may work through niche occupation and the generation of substances that are able to hamper the growth of pathogens (e.g., antibiotics produced by actinobacteria). An increased diversity of the microbiota is also the basis for a functioning food web, including protista and other eukaryotes, up to the earthworms. The activity of all these players contributes to the structural stability of soil, ranging from the formation of extracellular polymeric substances (EPS) by biofilm-producing bacteria, the structural network of actinobacterial and fungal mycelia to the secretion of mucilaginous substances by earthworms, strengthening the burrows. The co-occurrence of soil mineral and organic particles and EPS on one hand, and mycelia acting as a fiber-reinforcement on the other, makes resulting aggregates particularly strong.

In this context, the activity of soil fauna becomes important. Compost still contains digestible compounds, earthworms thrive and their burrows, strengthened by mucilaginous compounds, further contribute to the aeration and water conductivity of soils.

Climate related issues

The return of organic materials to soils is a natural way of closing nutrient and carbon cycles. The treatment process may, however, largely determine the climate-compatibility. The composting process releases CO_2, if managed properly. If aeration conditions are not maintained according to best practice, however, creation of considerable methane and nitrous oxide emissions can be a draw-back compared to anaerobic digestion (biomethanization) (Insam and Wett, 2008). Nevertheless, once applied to soil, several aspects contribute to the benefits of compost-based soil management regarding climate.

- Carbon sequestration. Under good process conditions, composting of organic wastes does generate CO_2 but not methane or nitrous oxide gas. The C remaining is in the form of some leftover plant material, (microbial) biomass and humic matter which is recalcitrant and may contribute to the buildup of long-lasting soil organic matter.
- The nutrients returned to soil substitute for chemical fertilizers that require a lot of energy for their production. The production of nitrogen fertilizer alone, based on the Haber-Bosch process consumes up to 2% of the global energy demand.

- Composts improve plant health, and in combination with organic agriculture, use of herbicides and pesticides may be averted.
- Soils amended with composts show an improved structural stability coupled with water retention, resulting in a reduced requirement for watering
- Improved water holding capacity may also help to reduce flooding that appears to become more frequent with climate change.

Conclusion

Nutrient and carbon cycling is a prerequisite for a sustainable economy and particularly concerning agriculture, horticulture and forestry. Bearing in mind the need for climate-friendly action and the need for maintaining healthy soils for the benefit of an increasing world population, composting is a way to get nutrient and carbon flows under control. Appropriately used, composts will render soils as sinks of greenhouse gases and make them less susceptible to erosion, increase their water holding capacity and microbial as well as faunal diversity and maintain their productivity on the long term. Moreover, composts may serve to convert waste lands to productive soils.

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