7.1. Introduction

It is difficult to define compost quality because the definition must take into account many different issues. Some of the most common issues generally are environmental and sanitary ones, while the issue regarding agronomic quality is undervalued. Strictly related to this attitude is the difficulty in the commercialization of compost since the material generally is considered more as a waste, that is, difficult to dispose rather than as a quality product with various and interesting market outlets. As far as the issue of its use in agricultural soils is concerned, amending soil by compost can be considered as a sustainable practice that directly and indirectly influences soil’s physical, chemical,
Compost science and technology

and biological fertility. Stability of organic matter plays an important role in influencing all aspects of soil fertility; as such, the main laboratory techniques used for determining stability must be described.

To become the object of a commercial transaction, compost should comply with specific and stable characteristics that make it a product with a reasonable level of competition with alternative fertilizer and amendment products. According to Martinez Orgado (2001), there are many barriers that affect the development of a real market for compost, the most important being the following:

- negative image of compost;
- possible presence of pollutants in compost;
- legislative and standards issues; and
- issues related with the structure of the market itself.

At the present time, it can be said that, in the strict sense of the word, there is not a real market for compost, but just a number of transactions (Martinez Orgado, 2001).

If attention is focused on the regulatory framework, frequent strong contrapositions between the Ministry of Environment (the one that generally regulates waste management) and the Ministry of Agriculture (the entity that regulates the commercialization of fertilizers) must be stressed. Indeed, at least in Western Europe, the latest regulations have played an important role in the growth of systems for the collection of wastes segregated at the source and the increase in the number of composting plants by establishing recycling targets. Modern laws regulating waste management generally aim at waste reduction, material recovery, reuse, and recycling, while landfilling is considered as one of the last options and only allowed for non-recyclable or properly treated materials. Environmental institutions at a national and local basis, especially in Mediterranean countries, in order to face a progressive decline in the organic matter content of agricultural soils, have planned to promote programs and subsidies to farmers for improving the recycling of organic matter. This approach should, theoretically, lead to a widespread use of compost and organic amendments in agricultural soils, while what actually happens is exactly the opposite due to environmental problems, more on emotional rather than on scientific bases.

As an example, European law on atmospheric pollution is very strict. The upper limit for the concentration of lead for continuous exposure has been set at 2 µg per m³. This limit is lower than that of other countries. If we accept that humans may live without appreciable problems when atmospheric air contains 2 µg Pb per m³, we also state that, given that 2 µg are 0.009651 μmol of Pb, i.e., 58.14 × 10¹⁴ atoms of Pb (by multiplying by Avogadro's number), a man who breathes 25 l of air per minute (typical value for light work) will inhale 1.445343 × 10¹⁴, i.e., 144,534,300,000,000 atoms of Pb per minute in his lungs without any problem, while an amount just 100 times higher, i.e., the inhalation of 1.445343 × 10¹⁶, i.e., 14,453,430,000,000,000 atoms of Pb per minute will be very toxic or lethal.

Of course, many explanations may be given to clarify the behavior of human lungs. The higher concentration of 1.445343 × 10¹⁶ atoms of Pb per minute may lead to lysis of lung tissues or of some specialized lung cells. Simply, the lower concentration
of $1.445343 \times 10^{14}$ atoms of Pb per minute may be easily cleared by the lungs, while the higher concentration may result in progressive accumulation in the lungs and/or their elimination together with feces or catabolic products. Over millennia, human beings have adapted to cohabit with several undesirable elements, and now they may live well together, below certain risk levels. These are the limits to maintain, while concentrations lower than the limits are not very useful and unsupported on any scientific ground.

7.2. Soil Fertility and its Improvement

7.2.1. Sustainable Agriculture and Composts

The main positive aspect of compost use in agriculture is probably related to the sustainability of this practice. The word “sustainable” refers to an agricultural activity of widespread use, even if sometimes it is misused. Indeed, sometimes it is associated with the reduction of agrochemical inputs, or to the application of some recent EC directive, or a recommendation made by the U.S. Environmental Protection Agency (US EPA). All of these interpretations are, of course, misleading, because none of them consider the most important aspect of a sustainable system or activity: the capability of maintaining itself for an indefinite period of time. The concept of sustainability must be considered in a broad sense: an activity or a system cannot be considered separately and isolated from other activities and systems. The production of compost gives to society as a whole the opportunity of closing the cycle of nutrients: compost derived from an agricultural activity must be returned to the soil if a sustainable and ecologically sound management of these materials is desirable (Sequi, 1996).

More specifically, compost use in agriculture can be considered as a sustainable activity because it simultaneously fulfills the following requisites stated by the OCDE (1992):

- to guarantee the conservation of environmental equilibria so as to allow the productivity to last on a permanently durable basis, i.e., it should not lead, in particular, to dissipation of non-renewable materials or energy (sustainability of resources),
- to guarantee full safety to the farmer and any other operator, in addition to hygienic and sanitary safe conditions to the consumer (sustainability of human health), and
- to guarantee economically convenient productions, i.e., a profit to farmers (economic sustainability).

Therefore, as a conclusion to what is stated above, one of the most important questions regarding the ability of a soil system for using compost is not related to the capacity of the soils to decompose organic materials of different origin but, among other aspects, to the total quantity that can be added to the soil before the system is overloaded. Too often compost is viewed as a disposal problem, rather than as a resource; indeed, this product could be considered as a good, cheap fertilizer and soil conditioner. The key to compost utilization is the full understanding of the main characteristics and the agronomic valorization of organic material of different origin (compost, biosolids) for the improvement of soil fertility.
7.2.1.1. Physical Fertility

The application of compost to soil is of considerable interest as a means of maintaining a suitable soil structure, as well as a means of adding organic material to soil whose organic matter content has been reduced by the practice of intensive agriculture, especially in the Mediterranean area (Legros and Petruzzelli, 2001). Many authors have shown improvements in soil properties such as structure (aggregation), Cationic Exchange Capacity (CEC), water-holding capacity, and permeability. Increases in soil organic carbon as a consequence of biosolids application were found correlated with lower bulk density, higher aggregation and aggregate stability, and water-holding capacity (Miller and Miller, 1999). Infiltration and hydraulic conductivity in soil amended with compost is more variable depending on time, rate, and method of application. Land application of compost on the soil surface may reduce hydraulic conductivity, while a simple technique of good agricultural practice like compost incorporation leads, over time, to an improvement of water infiltration due to a better aggregation and macro porosity.

Less surface crusting under rainfall, reduction of soil erosion in steep slopes, increase of water retention in sandy soils, and reduction of water logging and compactability of clay soils are some of the positive effects associated with the application of compost to agricultural soils.

7.2.1.2. Chemical Fertility

The evaluation of the agronomic value of compost is more difficult than that for mineral fertilizers. This is due to the complexity associated with the definition of specific parameters of quality to determine the benefits relative to land application of organic materials whose chemical composition is so variable. As indicated in the previous paragraphs, the simplest method of evaluating the agronomic value of compost is the calculation of the supply of organic matter and plant nutrients, particularly the macronutrient content of N and P. Crop yield response to an organic amendment, as with mineral fertilizers, follows the law of diminishing returns, so the agronomic value per unit of added material is higher to the farmer at low rather than high application rates (Parr and Hornick, 1993). The quality and quantity of organic matter added plays a key role in the determination of the agronomic value of land application of compost. Indeed, these characteristics influence the rate at which organic matter mineralizes in soil and, consequently, the great residual effects on soil fertility. The slow release of nutrients from the compost is responsible for the increase of crop yields in subsequent years and determines the difficulty in evaluating the true agronomic value of land application of compost.

The concentration of nitrogen in compost is probably the most interesting from either an environmental or an agronomic point of view, and this is the reason for using N content as the basis for calculating the application rates. Compost contains two forms of nitrogen, organic and inorganic. More than 85–90% of the total nitrogen content in
compost is organic, while the remaining 10–15% is inorganic and immediately available to the plants. The evaluation of the availability of nitrogen from the organic nitrogen fraction is more complex, depending upon many different factors. Some of the most important factors are: the amount of labile and stable organic compounds in compost and biological fertility of the soil. Moreover, in order to adjust the application rates of nitrogen fertilizers, inorganic and mineralized nitrogen already in the soil due to applications to the same field during previous years should always be considered (Miller and Miller, 1999). According to all of these parameters, it is possible to estimate the available N for compost in the first year of application as 30–35% of the total N content. The remaining part of the nitrogen that can be mineralized is considered to be available to plants in the following 2 years at a decreasing rate.

Phosphorus (P) is an essential plant nutrient and the low concentration (100–3000 mg P kg\(^{-1}\)) and solubility (<0.01 mg P l\(^{-1}\)) in soils make it a critical nutrient limiting plant growth. Even if inorganic phosphorus has generally been considered the major source of plant-available P in soils, the mineralization of labile organic P was demonstrated to be important in both low- and high-fertility soils and soil microbial biomass to play an important role in P cycling (Tate et al., 1991).

Compost contains on average 0.6–2.0% P (dry matter) and, generally, at the application rates determined to satisfy crop nitrogen need, is sufficient to cover P plant uptake. After application of compost to soil, the P is distributed in the uppermost layer (0–30 cm) as total P, while, at higher doses, available P increases at 0–45 cm (Genevini and Mezzanotte, 1987). Compost usually is characterized by a low concentration of potassium and its contribution to plant nutrition is negligible.

### 7.2.1.3. Biological Fertility

Due to its particular physico-chemical characteristics, compost represents an ideal substrate for the growth of many different microbial groups (Benedetti, 2004). Compost may contain pathogens like bacteria, viruses, fungi, and parasites, but numerically they are a negligible fraction of the total microbial population (de Bertoldi et al., 1991). So, the relatively large number of native saprophytic microorganisms play an important role in pathogen control during composting through microbial competition and antagonism for nutrition.

The microbiology of composting is extremely complex, being characterized by the succession of microbial communities selected by a continuing change of environmental conditions determined by previous activity (Miller, 1993). Bacteria, actinomycetes, and fungi have been specifically identified during the composting process, but what is more important in terms of soil biological fertility is that microbial communities in compost belong to the physiologic groups of cellulolytic, pectinolytic, proteinolytic, nitrifiers, and so on which contribute, as a whole, to the cycling of soil nutrients. Moreover, saprophytic microorganisms in compost represent a supply of organic carbon and nitrogen that can be easily mineralized for soil microbial biomass.
7.2.2. Behavior of Heavy Metals in Soil

Among the possible negative effects of compost utilization, the potential release of toxic heavy metals into the environment and the transfer of these elements from the soil into the food chain generally are claimed as the most relevant. A thorough evaluation of these effects may be supported by the knowledge of the behavior of the heavy metal in the soil environment. The concentration of heavy metals in the compost generally is higher than the normal concentration in soil, and the possibility exists of the accumulation of metals in the soil with consequent negative effects on water quality and the food chain. The environmental hazards are strictly linked to the mobility of metals, and thus to their concentration in the soil solution. This is why the distribution of heavy metals between the soil solid phase and the soil solution is considered of paramount importance in evaluating the environmental consequences of adding materials containing heavy metals to soil.

An increase of heavy metal concentration in the soil solution increases plant uptake and leaching, but the environmental hazards can be drastically reduced if the metals are retained in the solid phase of soil. This problem is particularly important in the distribution of compost on the land both in agricultural utilization and in landfill disposal.

Since fundamental processes may arise in the soil that move heavy metals into the food chain, it seems essential to investigate the behavior of metals in soil and their chemical speciation and to determine, as far as possible, the physical–chemical parameters that control their form and distribution, particularly in the biologically active pools. This distribution is controlled by a complex series of reactions in dynamic equilibrium, and influenced by the chemical, physical, and biological characteristics of the soil, the characteristics of the compost, the climatic conditions, and the agronomic techniques.

The main factors that affect the environmental behavior of heavy metals are pH, cationic exchange capacity, organic matter, water, and the thermal regime of the soil.

The activity of a metal ion in the soil solution depends directly or indirectly on the pH. The specific adsorption sites depend on pH and any increase in acidity reduces the number of sites available for the heavy metals.

Cationic exchange capacity (CEC) regulates the mobility of metal ions. Being a measurement of the negative charge on the constituents of the soil, CEC is an index of the soil capacity to adsorb and hold metal cations. Both organic matter and clay minerals contribute to CEC. The CEC derived from clay generally is little influenced by pH, unlike the CEC derived from organic matter.

Humic substances can interact with metals forming complexes and chelates of varying stability. The complexing ability of humic substances essentially depends on the content of functional groups containing oxygen and on amino and imino groups. Complexes of the heavy metals with soil organic matter can have different solubility and therefore a different environmental mobility.

The use of compost-containing metals in different chemical forms and organic matter of varying structures able to complex them, and the possible variations of pH induced in soil can change the distribution of heavy metals in the various complexes and can
Table 7.1. Chemical forms of heavy metals in soil

<table>
<thead>
<tr>
<th>Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Simple or complexed ions in soil solution</td>
</tr>
<tr>
<td>b. Exchangeable ions</td>
</tr>
<tr>
<td>c. Linked to organic matter</td>
</tr>
<tr>
<td>d. Occluded and co-precipitated with oxides, carbonates, and phosphates or other secondary minerals</td>
</tr>
<tr>
<td>e. Ions in the crystalline lattices of primary minerals</td>
</tr>
</tbody>
</table>

Therefore modify their availability to plants. Roots, in fact, are not only able to absorb free ions present in soil solution, but can also interact with the weakest metal–organic matter complexes.

Soil water and thermal regime influence the redox processes of heavy metals and the more general decomposition processes of compost organic matter. The depth of soil tillage also is important as it determines the nature of the contact and the reactions between metals and soil constituents. As reported in Table 7.1, heavy metals in soil can be present in various chemical forms.

The first three chemical forms are in equilibrium and effectively available for plant nutrition, and environmentally significant. The main reactions that lead to the distribution of heavy metals in these different pools follow.

Hydrolysis

In soil solution, metal ions are mainly coordinated to water molecules and thus remain in a free form; however, in the presence of available ligand, the formation of more stable complexes prevails. Hydroxyl complexes are the most abundant, because heavy metals easily hydrolyze in the normal pH range in soil. The products of hydrolysis can further release more protons from the coordinating water molecules. In fact, the equilibrium constant indicates the strong influence of the pH, which is determined both from the soil and the characteristics of the waste.

Complex Formation

The formation of complexes between a metal ion and an uncharged ligand in the soil solution can lead to a complete displacement of the water molecules, assuming that the coordination number of the metal does not change. The humic molecules play a specific role in this type of reaction, in which the “donor” atoms are oxygen in carbonyl, carboxyl, and hydroxyl groups, and nitrogen in amino groups. The addition of compost may also increase the concentration of some anions such as chloride and nitrate phosphate, which are able to complex heavy metals. Moreover, compost can contain organic molecules that are capable of forming more or less stable complexes with the metal ions, and more or less soluble in relation to molecular weight, pH, and concentration of ligands, given the presence of dissociated functional groups.
Redox Potential

The speciation of heavy metals is considerably influenced by redox reactions, both of a chemical nature and of microbiological origin. Iron and manganese oxides, which generally occur in soil as mineral coatings and nodules, play a role of particular importance in this type of reaction. In general, heavy metals are less soluble in their highest state of oxidation. Therefore, the capacity of the iron and manganese oxides to oxidize the metals contributes to a decrease in their solubility and mobility in the environment.

Precipitation and Adsorption Reactions

The various chemical species of heavy metals in the soil solution are in equilibrium with those retained in the solid phase. The possibility for an ion or a soluble complex to remain in solution depends on many factors, such as the concentration of the metal and of other competing cations, the concentration of ligands and chelating agents able to form complexes, the pH, and the nature and quantity of adsorption sites present in the solid phase.

Displacement from solution can occur essentially by means of either precipitation or adsorption. Depending on the process involved, which is strictly connected to soil conditions and to the kind of biomass added, there is a variation in the type and intensity of the forces involved that maintain the ions in pools that are more or less immediately available to root absorption or to leaching. It is typical of heavy metals to be involved both in normal cationic exchange reactions (principally connected to the charge characteristics of the ion and to coulombian-type attractions) and in specific interactions involving various factors such as the geometry of the adsorption site, the size of the ion and the co-ordination number, the hydration energy, and the ability to polarize.

7.2.3. The Importance of Compost Quality

The variety and complexity of physico-chemical and biological components in compost and in a soil system affect the possibility of studying the effects of the addition of organic materials into the soil. Indeed, it is difficult to distinguish between the direct and the indirect effects of an amendment on soil microbiological activity. In soil amended with compost, soil respiration can be stimulated as a consequence of the addition of either labile organic matter, which increases autochthonous microbiological activity or of the microbiological activity of heterotrophic microorganisms introduced. Organic nitrogen compounds are mineralized according to the same mineralization pattern shown for organic carbon, since in most of the organic nitrogen compounds C/N are covalently bound. On the other hand, in organic compounds containing sulfur and phosphorus, S and P atoms are released by simple enzymatic hydrolysis without a specific mineralization process of the organic matter.

As stated above, if labeled materials are not used, it is still difficult to determine if mineralization products like $\text{CO}_2$, $\text{NH}_4^+$, $\text{SO}_4^{2-}$, and $\text{PO}_4^{3-}$ derive from the mineralization of native organic matter or from the added organic material.
7.2.3.1. Biological Stabilization of Organic Matter

One of the key issues in defining compost quality is the evaluation of the stability of the organic matter in the material. For this reason, it is necessary to segregate and set up analytical methods capable of following the transformation of the organic matter during the composting process and to determine the level of stability reached. During the composting process due to a combination of biological and chemical transformations, the amount of fermentable organic compounds progressively decreases while the relative content of humic (or humic-like) compounds increases. Respiration index (RI), humification rate (HR%), and humification index (HI%) determinations have been demonstrated to be effective indicators of the residual amount of labile organic matter in compost (HR%) and of the formation of humic-like substances during compost maturation (HI%), being able to establish with accuracy the moment of complete stabilization (Ciavatta et al., 1990; Scaglia et al., 2000).

Another chemical technique able to characterize organic matter of composted amendments is isoelectric focusing (IEF) (Ciavatta et al., 1993). This technique allows to fractionate the organic compounds on the basis of their isoelectric point and their electrophoretic mobility. IEF was utilized to obtain information on the qualitative characteristics of organic matter in soils (Ciavatta and Govi, 1993), amendments, and organic fertilizers (Ciavatta et al., 1997; Canali et al., 1998).

Also, thermal methods of thermogravimetry (TG) and differential scanning calorimetry (DSC) have been successfully used for the assessment of maturity in compost, as a comparative method in evaluating the evolution of organic matter (OM) during the composting process (Blanco and Almendros, 1994, 1997; Dell’Abate et al., 1998, 2000; Dell’Abate and Tittarelli, 2002). DSC and TG are techniques based on the physico-chemical reaction to temperature of substances that, according to their chemical composition and structure, show a peculiar pattern of thermal stability. Thermal analysis techniques, when applied to amendments, provide useful information on the quality of organic matter and, consequently, can be used in the assessment of its maturity level. TG and DSC can be applied on whole compost samples and thus allow the analysis of the thermal stability of organic matter within the mineral matrix to which it is closely associated. These represent a potential analytical advantage with respect to the chemical methods for the characterization of the organic matter in compost reported in a previous section, which need extraction and fractionation procedures of different classes of C compounds, to overcome the problem of the production of artifacts.

Following is a brief description of the methods presented in the previous section.

Respiration Index

The respiration index can be determined according to a static and/or a dynamic approach. The dynamic approach is considered, by far, more reliable than the static one because oxygen is never a limiting factor. The dynamic respiration index is determined by quantifying the hourly consumption of oxygen of a tested organic material by the utilization of a continuous air flux respirometer. Compost to be tested undergoes continuous aeration...
adopting air fluxes capable of guaranteeing a concentration of oxygen always higher than 14% (v/v), in the air discharged from the respirometer. The test is carried out for a period of time ranging from 1 to 4 days, according to the lag phase time, by detecting the index value every 2 h.

**Extraction and Fractionation of Organic Matter**

The extraction is carried out on compost samples of 2 g each with 100 ml of a solution NaOH/Na4P2O7 0.1 N for 48 h at 65°C. Samples are centrifuged at 2500 rpm and the supernatant solution is filtered through a 0.45 µm Millipore filter. Extracts are stored at 4°C in a nitrogen atmosphere.

Humic and fulvic acids are fractionated by acidification of 25 ml of the extract with H2SO4 50%, separating humic-like acids (HA) (precipitated) from fulvic-like acids (FA) (in solution). The fulvic-like acids are purified on a polyvinylpyrrolidone (PVP) column, resolubilized with NaOH 0.5 N, and then joined to the humic portion. Combined fractions (HA + FA) are quantitatively transferred into a calibrated 50-ml flask, brought to volume with NaOH 0.5 N, and stored at 4°C under a nitrogen atmosphere. The total organic carbon (Corg) in compost samples can be determined according to Springer and Klee (1954). Total extractable carbon (Cextr) and humic and fulvic acids carbon (CHA + FA) are determined following the procedure proposed by Ciavatta et al. (1990). Humification parameters for assessment of organic matter stabilization in compost are calculated as follows:

\[
\text{Humification rate (HR) percent} = \left(\frac{\text{CHA} + \text{FA}}{\text{C}_{\text{org}}} \times 100\right)
\]

\[
\text{Humification index (HI)} = \frac{\text{C}_{\text{not humified}}}{\text{CHA} + \text{FA}} = \left(\frac{\text{C}_{\text{extr}} - \text{CHA} + \text{FA}}{\text{CHA} + \text{FA}}\right)
\]

**Isoelectric Focusing (IEF)**

Isoelectric focusing separations for compost samples can be carried out in a Multiphore II, LKB electrophoretic cell, according to Govi et al. (1994). Ten milliliters of NaOH/Na4P2O7 extract are dialyzed in 6000–8000-Da membranes, lyophilized, and then separated on a 5.06% T and 3.33% C polyacrylamide slab gel, in which a pH range of 3.5–8.0 was created using a mixture of carrier ampholytes (Pharmacia Biotech): 25 units of ampholine pH 3.5–5.0; 10 units of ampholine pH 5.0–7.0; 5 units of ampholine pH 6.0–8.0.

A pre-run (2 h; 1200 V; 1°C) is performed and a specific surface electrode checks the pH gradient formed in the slab. The electrophoretic run (2 h 30 min; 1200 V; 1°C) is carried out loading the water-resolubilized extracts (1-mg C 50 µl−1 sample−1). The bands obtained are stained with an aqueous solution of Basic Blue 3 (30%) and scanned by an Ultrascan-XL Densitometer. In order to compare isoelectric focusing data, the same operative conditions must be applied for IEF separations.

**Thermal Techniques**

DSC and TG are carried out with a Netzsch Simultaneous Analyzer STA 409 equipped with a TG/DSC sample carrier supporting a type S thermocouple of PtRh10-Pt. This device
is considered capable of calorimetric measurement and is named “heat-flux DSC,” where DSC means differential scanning calorimetry, being the quantity \( M = \frac{\text{area under peak}}{\text{latent heat of fusion per gram} \times \text{Sample Mass}}, \) a constant for transformation in series of different standard materials.

In particular, in a heat flux DSC, the temperature difference between the sample and the reference material is recorded as a direct measure of the difference in the heat-flow rates to the sample; in TG, the weight change of a sample is measured during the thermal program. The first derivative of TG trace (DTG) represents the weight loss rate (expressed as \% \text{min}^{-1}) and is calculated in order to better distinguish among subsequent decomposition steps.

Samples are analyzed without any pretreatment, except for manual grinding in an agate mortar. The following conditions are adopted: heating rate of 10°C per min from 20 to 1000°C, oxidizing atmosphere for static air, alumina crucible, calcined kaolinite as reference, and sample weight about 35 mg.

### 7.2.4. Phytotoxicity and Food Chain Compatibility

#### 7.2.4.1. Heavy Metals

Heavy metals in compost may derive from both the contamination of different kinds of wastes containing high concentrations of these elements and the leaching of metal wastes carried out by organic acids produced during composting. To deal with the problem of heavy metals in compost, it is particularly important to determine the source of these elements in the wastes. The variability of composition of the compost is considerable, given that the amount and the nature of the wastes depend on geographical and social conditions. However, as a general rule, it is possible to consider the distribution of heavy metals in urban wastes similar to that described in Table 7.2 (Rosseaux, 1988).

Almost all of the components of urban wastes contain heavy metals. Cadmium and zinc, in the form of oxides and hydroxides, are present in high quantities in small batteries, and lead oxides in car batteries, whereas metal sulfides (CdS, ZnS) are commonly found in the dyes and stabilizers of plastics. Lead and zinc oxides are very common in the wastes coming from textile materials, whereas metal salts, such as sulfates and chlorides, can be found in various types of wastes.

<table>
<thead>
<tr>
<th>Table 7.2. Distribution of heavy metals in different types of wastes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
</tr>
<tr>
<td>Chromium</td>
</tr>
<tr>
<td>Nickel</td>
</tr>
<tr>
<td>Lead</td>
</tr>
<tr>
<td>Zinc</td>
</tr>
</tbody>
</table>
Relevant changes have occurred during the last few years. The elimination of mercury from most batteries has brought about a drastic reduction of this element in urban solid wastes. The data on wastes produced in France indicate that the quantity of mercury fell from 270 tons in 1985 to 35 tons in 1993 (Amman, 1993).

A suitable selection of the wastes coming from a correct source-separated collection can therefore substantially reduce the potential risks deriving from heavy metals. The effects of different contaminant separation methods on the heavy metal content of compost are reported in Fig. 7.1.

In particular, to help the development of the composting process and in order to obtain good qualitative characteristics of the final product, it is important to obtain a suitable separation of the organic matter. The separation of the organic fraction at source positively affects the metal content of the compost obtained (Golueke and Diaz, 1991; Spencer, 1994). However, we cannot ignore the possibility that a certain amount of metals might also be present in the compost coming from source-separated materials. The heavy metals, in the presence of fermentable organic matter in the particular leaching environment created following microbial activity, migrate into the biodegradable matrix without any further possibility of being separated.

From an environmental point of view, in addition to the total concentration, it is also important to know the chemical species that metals assume in the soil. Heavy metals, in fact, can be present as salts (carbonates, sulfites, etc.), bound to organic matter, or in an adsorbed or exchangeable form. The predominance of one chemical species over all others depends on the origin and type of metal, and on the composting process. Cationic species have a different mobility than complexed species, which often are chelating agents like humic-like substances with a considerable variety of molecular weights. The nature of the metal considerably affects the behavior of these elements in the soil.
7.2.4.2. Influence of Heavy Metals on Soil Quality

Concern with regard to the heavy metal pollution of agricultural soils is essentially related to the crop quality and human health. The most pertinent question is to determine if the application of compost results in a deterioration of soil quality by increasing the original concentration of heavy metals. The addition of compost, especially if derived from municipal solid wastes, can increase the metal content of the agricultural soils, due to the higher concentrations of metals in the biomass. However, if compost is mixed into the plough layer of non-acidic soils, metals do not leach appreciably and the bioavailable chemical fraction usually does not increase, even though the chemical form of the metals is not predictable in the long term.

Organic matter appears to play different roles in controlling the availability of trace metals. Immediately after the application of sludge or compost to soil, there could be an increase in bioavailability, both due to the rapid decomposition of organic matter, that may release soluble metals (Chaney and Ryan, 1993), and to the incomplete initial mixing of biomass with soil. This produces a situation of non-equilibrium, in which the soil adsorbing properties are not completely effective.

Moreover, according to the molecular complexity of humic-like materials in compost, some metal cations, such as Cu^{2+}, are strongly bound and thereby are prevented from diffusing to the roots, while organic materials of different kinds form complexes with heavy metals. Thus, plants are not always able to extract trace metals (Petruzzielli et al., 1977; McBride, 1994).

The complexes of heavy metals with soil organic matter can be sub-divided depending on their solubility, which determines their environmental mobility, as reported in Table 7.3.

Field experiments showed that, with time, the levels of mobile metals added with compost or sludge stabilize at lower values, and bioavailability is reduced. The phenomenon has been ascribed to the adsorptive properties of biomass, which can prevent an excessive heavy metal uptake by plants. But can this protection, attributable to the added organic matter, be considered permanent and effective for all toxic metals in the long term?

Studies concerning the protective effect of sewage sludge reached opposite conclusions. Chaney and Ryan (1993) stated that the specific metal adsorption capacity added with sludge will persist as long as the heavy metals persist in the soil, but McBride (1995)

<table>
<thead>
<tr>
<th>Table 7.3. Complexes between organic matter and heavy metals</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Organic matter of high molecular weight, containing aromatic nuclei condensed in polymer complexes, which have a very high affinity for heavy metals and which are, for the most part, insoluble</td>
</tr>
<tr>
<td>b. Organic matter of recent origin of low molecular weight, essentially deriving from the breakup of microbial cells, roots, etc.; they represent the primary units for the formation of humic components of a higher molecular weight and generally exhibit high solubility</td>
</tr>
<tr>
<td>c. Soluble organic matter, which forms insoluble salts reacting with the metals</td>
</tr>
</tbody>
</table>
Compost science and technology

rejected the argument suggesting that the slow mineralization of organic matter in soils treated with sludge could release metals in more soluble forms.

Understanding the adsorbing processes is fundamental in order to assess the effects of biomass on soil quality. When the soil is treated with organic biomass, the metals are adsorbed not only onto the soil but also onto the organic matter deriving from the waste materials. Such substances, previously adsorbed on the soil, give rise to new adsorbing sites with a higher affinity for the metals. As an example, the distribution coefficient of Ni is reported in Fig. 7.2 (Petruzzelli et al., 1992).

At a low concentration, the metal is mostly held by the soil treated with sewage sludge. As the adsorbing sites gradually become saturated, the distribution of the metal between the solid and liquid phases returns to the values of the untreated soil. Analogous behavior, i.e., an increase in the amount of metal held by the soil and a modification of the type of isotherm, was observed for cadmium, zinc, lead, and copper (Petruzzelli et al., 1994).

It is important to stress that the sorption capacity is inversely related to the amount of metal sorbed, so that a biomass with a low concentration of metals is more suitable to providing new sorbing sites. However, the adsorbing capacities decrease when the “covering” of the soil adsorbing surfaces by heavy metals increase.

A similar process can also be reasonably hypothesized when compost is added to soil. Long-term studies were conducted to evaluate the sorption properties of a soil which had been treated for 5 years with a high rate of composted sludge (Petruzzelli et al., 1997). Once the period of addition of composted sludge ceased, the soil remained untreated for 15 years so that it was possible to evaluate the residual effect of composted sludge.

![Fig. 7.2. Pattern of Ni distribution coefficient, with (K\textsubscript{d,ss}) and without (K\textsubscript{d,os}) sewage sludge, as a function of metal sorbed by the soil \(q\) (mol g\(^{-1}\)).](image-url)
addition on the sorptive capacity of the soil. Zinc and cadmium were selected as heavy metal models.

In the untreated soil, the isotherms of cadmium and zinc reached saturation and can be classified as “L type” (Petruzelli et al., 1977). This kind of isotherm corresponds to a great affinity between the metal ions and the sorbing surfaces, which selectively favors heavy metal sorption with respect to alkaline ions. In the soil treated with composted sludge, the isotherms still are of the “L type,” but they are characterized by an increase in the sorption capacity.

The results obtained for these metals indicate that, after the addition of the composted sludge to the soil, the solid phase showed a greater affinity for the metals, since the amounts sorbed were higher than in the original untreated soil at any concentration used. A possible explanation for these findings is that new sorbing sites become available on the solid phase of the soil following the addition of composted sludge (Szymura et al., 1990; Petruzelli et al., 1992), and that these sites were still active 15 years after the cessation of sludge addition to soil.

These results confirmed previous findings of laboratory sorption trials carried out on the same soil in which it was shown by a detailed analytical characterization (NMR, IR, and HPLC) that soil was able to retain different organic compounds after mixing with a sludge extract (Gennaro et al., 1991; Petruzelli et al., 1994).

The degree of changes that might occur in the soil properties seems to be related to the properties of the composted sludge added. Compounds of an organic nature deriving from the composted sludge sorb on the soil, providing new sorbing sites to heavy metals. The metal bonding by the organic functional groups can be supposed to be not only an ion exchange, but that some metals coordinate directly, as the high degree of selectivity shown in the sorption process suggest.

The sorption isotherms can be described adequately by the Langmuir equation in the form of (Soon and Bates, 1982):

$$q = \frac{q_mKC}{1 + KC}$$

where $q$ (µg/g) is the amount of metal sorbed per unit weight of soil, $C$ (µg/ml) is the equilibrium concentration, $q_m$ (µg/g), and $K$ (ml/µg) are adjustable parameters related to the maximum sorption and to the energy of sorption.

The Langmuir approach to the sorption phenomena, one of the most commonly used in soil chemistry, is based on the assumption that the bonding energy of all sorbing sites is uniform. This is often not true in soils, where more than one type of reacting surface exist; however, whenever the sorption reactions approach saturation with increasing concentration, the conditions allow approximation of the description of sorption with a Langmuir type equation (Petruzelli et al., 1977).

Even if the Langmuir model has some theoretical limitations, it is very useful, since it allows a comparison of the sorption maxima “$q_m$” for the different metals, and permits a quantitative evaluation of the effect of the composted sludge on the sorption capacity.
of the soil with respect to the untreated soil. The Langmuir parameters obtained in this experiment are reported in the Table 7.4.

These findings support the hypothesis that the sorptive properties of composted sludge can prevent the release of heavy metals and their excessive uptake by crops.

This protective effect can be attributable largely to the added organic matter, and can be considered effective even for a long time (15 years) after the cessation of biomass addition. In this experiment, the amount of organic matter in treated soils is unchanged from the end of biomass addition. Moreover, inorganic materials of sludge (carbonates, oxides, phosphates), are also known to be able to retain metals in relatively insoluble forms (Petronio et al., 1993).

In this field, experimental organic matter in the plots treated with composted sludge was still higher than in the control plot. The residual organic matter can, therefore, play an essential role in retaining heavy metals and in increasing soil sorptive properties. These metals, in turn, can protect organic matter by exerting a toxic effect against the microorganisms, which are able to decompose humic-like materials (Minnich and McBride, 1986).

Following the interruption of biomass application, a fairly constant extractability has been generally observed (McGrath, 1987) and sometimes a slow change in the bioavailability (Davis and Carlton-Smith, 1984) of heavy metals. In some cases, it has been shown that about 30% of organic matter derived from sewage sludge remained in the soil even if the application had stopped more than 20 years earlier.

### Table 7.4. The Langmuir parameters for control (os) and treated (ss) soil

<table>
<thead>
<tr>
<th>Metal</th>
<th>$q_m$ (µg/g)</th>
<th>$K$ (ml/µg)</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn os</td>
<td>87.1</td>
<td>$1.81 \times 10^{-2}$</td>
<td>0.9877</td>
</tr>
<tr>
<td>Zn ss</td>
<td>152</td>
<td>$5.95 \times 10^{-2}$</td>
<td>0.9943</td>
</tr>
<tr>
<td>Cd os</td>
<td>65.9</td>
<td>0.181</td>
<td>0.9861</td>
</tr>
<tr>
<td>Cd ss</td>
<td>84.4</td>
<td>0.119</td>
<td>0.9993</td>
</tr>
</tbody>
</table>

7.2.4.3. *Organic Contaminants*

The composting of organic matter is a complex mixture of biological and chemical reactions that produces many products: stabilized solid, volatile compounds, carbon dioxide, water, and heat.

Organic matter has a self-limiting control on these products, and the evolution of these compounds depends on the origin, composition, structure, and microflora present in the material during the process (Chanyasak et al., 1982). Different strategies and technologies have been developed for controlling the composting process; some remove heat by blowing air through the composting mass, using a temperature set point as control (Finstein et al., 1983), while others blow air following oxygen behavior to maintain a specific oxygen level within the biomass. Various problems in the application of these systems still exist...
as the air used to accomplish temperature or oxygen control also changes the conditions for development of the microbial populations involved in organic matter transformation; often, these control systems produce the interruption of organic matter degradation.

During composting, many organic compounds can be degraded by microbial action, distilled by an increase of solid temperature, stripped by water emission, and modified by heat and chemical reaction. For these reasons, composting can be used for the remediation of biomass or soils associated with pollution. Until now, bioremediation is described as an “emerging technology” as an alternative to landfarming and incineration (Crawford et al., 1993), although some events have increased the awareness of the potential for biological remediation by onsite treatment (in situ, prepared bed, and bioreactor systems) in conjunction with chemical and physical process.

For composting, depending on its nature, the waste can be mixed with a “solid bulking agent” to improve porosity and possibly also to supply a supplementary metabolizable substrate. The material undergoing composting is thus a nutrient, a source of water, and a heat sink.

Once environmental conditions have been optimized, the ubiquitous distribution of microorganisms allows, in most cases, for a spontaneous enrichment of the appropriate biodegrading microorganisms (Cerniglia, 1984). In the case of toxic compounds, inoculation with pre-adapted microbial cultures may at times hasten biodegradative cleanup. The level of cleanup depends on two factors: (1) the ability of microorganism enzymes to accept substrate compounds with structures that are similar, but not identical to chemicals found in nature; and (2) the ability of novel substrates to induce or repress the synthesis of the necessary degradative enzyme in the microorganisms.

The biological fate of a novel compound may be: complete mineralization, partial degradation, accumulation, or polymerization. Compounds that are completely degraded — mineralized to carbon dioxide, water, ammonia, sulfates, and phosphates — are usually metabolized by a complete metabolic pathway and can be utilized as a source of carbon and energy by the microbial community. Those degraded to a greater or lesser extent are usually transformed as a result of a co-metabolism.

Almost all environments possess a diverse population that results in the degradation of so many xenobiotic compounds. A particular organism may possess the right catabolic ability to catalyze the transformation of one compound but then may not possess the enzymatic system for further degradation. These may be supplied by a second organism and so on, so that communities of organisms possessing complementary catalytic capabilities are established and the compound is degraded.

The synergistic degradation of a xenobiotic compound can also prevent the buildup of toxic intermediates, as in a number of instances partial degradation leads to the production of a compound more toxic to the natural community than the original substrate.

By the utilization of the natural detoxification pathways present in microbial communities, the pollution control industry has harnessed, or is planning to harness, microbes for waste management, particularly for the control of the organic pollution and especially haloorganic compounds and aromatic hydrocarbons.

Composting has been used to treat a solid phase material. However, in reality, the polluted starting materials considered may be of three basic types: soil, groundwater,
Compost science and technology

and slurry. The term “soil” encompasses a far broader range of materials, including, but not limited to topsoil, subsoil, and other natural regolith, fill, waste deposits and industrial process residues, sediment, demolition debris, vegetation, and refuse.

Groundwater and slurry may be mixed with a solid bulking agent to maximize microbial activities through control of process conditions: moisture content of the matrix, pH, temperature, oxygen supply, and elemental ratios. The type of organic amendments used and the ratio of contaminated soil to organic amendment are crucial parameters in making this technique cost-competitive with other disposal and treatment technologies.

Bioremediation is among the most inexpensive methods for the detoxification of soils contaminated with organic compounds, and composting is intermediate in cost among the bioremediation technologies. When comparing the total budget for cleanup of a large site, the savings associated with the use of bioremediation versus chemical- or physical-based technologies give bioremediation an overwhelming monetary advantage.

Compost bioremediation has proven effective in degrading or altering many types of contaminants, such as chlorinated and non-chlorinated hydrocarbons, wood preserving chemicals, solvents, heavy metals, pesticides, petroleum products, pharmaceutical waste, and explosives (US EPA, 1997).

Most of the experiments focused on the composting process have found that up to 30% of contaminated soil (by volume) could be mixed with compostable materials, whereas higher inclusion of contaminated soil in a composting mix resulted in sub-thermophilic temperatures and reduced degradation of contaminants.

A common complaint about solid-phase bioremediation methods is that they are too slow. For example, commonly used procedures for bioremediation of petroleum-contaminated soils require several months to a year to achieve cleanup, a time scale that may be in excess of established deadlines. Before composting can be widely accepted as a remediation technology, several issues need to be resolved: the materials being composted affect the degradation rate of specific contaminants; a relatively low extent of mineralization of aromatic compounds occurs in compost. When properly handled, however, field-level composting can reduce contaminants to undetectable levels with an extremely low occurrence of toxic intermediates (Civilini and Sebastianutto, 1996; Civilini et al., 1996). On the other hand, formation of linkages between humic materials and metabolites results in relatively long-term stabilization of the metabolite in a form of low bioavailability. If the metabolite is incorporated into the core structure of the humic acid, the residence time of the metabolite-derived carbon will be decades to centuries.

Additional information about bioremediation is presented in the following chapter.

### 7.2.5. Agronomic Utilization of Compost

Compost can be used in different quantities and ways according to its final destination. Among the most important applications of compost are the following:

- open field amendment;
- nursery; and
- landscaping.
For each field of utilization, the most important physico-chemical characteristics of
compost can be optimized. A further use of compost concerns the application for soil
reclamation purposes.

7.2.5.1. Open Field Amendment

Open field utilization of compost should be considered in the technical framework of
organic amendment and should follow principles of good agricultural practice regarding
organic fertilization. As reported above, organic matter plays an important role in soil
fertility as a whole. In particular, even if organic matter in organic amendments is mainly
used for improving chemical and physico-mechanical characteristics of soil, compost
application to soil determines an increase in nutrients load. Nutrients are originally present
mainly in an organic form and, as a consequence of mineralization processes, are released
in an available form for plants. Net mineralization takes place in soil at a different rate
according to: the degree of stability of the organic matter in the compost, soil biological
fertility, and climate. So, the ideal characteristics of an organic amendment like compost,
for open field utilization, could be summarized in the following points:

- high concentration of organic matter,
- high degree of organic matter stability (high content of humic-like substances), and
- low content of nutrients in order to increase the amount of compost added to soil and
  enhance its amendment role.

7.2.5.2. Growing Medium for Nurseries and Greenhouses

Even if economic competitiveness of compost is evident when compared with peat or with
growing media based on peat, from a technical point, peat cannot be easily substituted by
compost. Nursery and greenhouse growers routinely use a technique based on the inte-
gration of the growing media with mineral fertilizers. Peat has stable physico-chemical
characteristics and low nutrient values and these characteristics make it difficult to sub-
stitute. Heterogeneity of matrices and process technologies utilized make, on the other
hand, the physico-chemical composition of compost extremely variable, which hampers
a total substitution of peat, but allows for the complementarities of their characteristics so
that compost can be mixed with peat.

The use of compost in a nursery and greenhouse-growing regime should be driven by
the consideration of the following general characteristics:

- pH;
- salinity;
- pore space and water content; and
- water-holding capacity.

Many of the characteristics of compost reported above are strictly connected and need
to be carefully taken into account.
pH and Salinity
Most containerized nursery and greenhouse plants require growing media whose pH falls between 5.5 and 6.5. Since compost has a neutral to alkaline pH (7.0–9.0), which could potentially increase the final pH of the potted growing medium, special care should be taken to limit the total amount applied to each container.

Salinity is another parameter that can become a limiting factor in the use of compost in nursery plants because roots cannot escape from toxic level of salts in the relatively small volume available. To avoid damage to plants when using compost, total soluble salts in the final blend should not exceed 1.5 dS/m for nursery crops and 2.0 dS/m for greenhouse crops. To achieve this, composts used in blends for containers or greenhouses should be characterized by a low content of nutrients, like green compost, and mixed in a low percentage with bark and other additives (moss, perlite, etc.) when derived by rich matrices.

Pore Space, Water Content, and Water-Holding Capacity
The particle size of compost is extremely important in determining porosity and water retention. As the particle size in compost decreases, the blend will be less porous, but, on the other hand, more water will be retained. Alternatively, if the particle size is too coarse, water retention will decrease and available oxygen to the roots will increase. So, the blend should balance the different physical properties reported above in order to achieve a stable anchor to the roots, enough pore space for root respiration and sufficient water retained and easily available. For these reasons, compost should be screened to a minus 2 cm size for potted plants with a low percentage (about 25%) of the total volume as small particles in order to guarantee optimal physical characteristics and a constant level (roughly 40–60%) of water retained.

7.2.5.3. Landscaping
Compost can be used as soil amendments for turf establishment and landscaping. Many potential benefits are derived from landscaping with soils amended with compost:

- increased water retention;
- increased nutrient retention;
- decreased pesticide needs;
- reduced stormwater runoff; and
- reduced soil erosion in steep slopes.

The recommended procedure for any landscaping purposes (lawns, ornamental vegetation, and flowerbeds) is based on a soil amendment resulting in a 20 cm soil base having an organic matter content between 8 and 12%. In order to succeed in the establishment of lawns, the compost used should be characterized by a high content of well stabilized organic matter and with a high content of humic-like substances in order to reduce potential phytotoxicity on young roots of the turf as much as possible.
7.2.5.4. **Soil Reclamation**

Compost can be effectively used for soil reclamation and decontamination. In every reclamation project, as well in any decision involving the protection of the public and the environment from the adverse effects of pollutants from natural and man-made sources, preliminary collection, evaluation, and use of environmental data are essential. Decisions concerning environmental and human health protection often result in requiring operation of pollution control or remediation systems as alternatives to the natural attenuation approach. Environmental technologies are required in order to reduce contamination levels in the environment and to maintain the levels at concentrations that do not threaten the environment or human health and safety. Several specifications for quality management functions and activities are necessary to support environmental programs. Such programs may include: (1) characterization of environment systems in terms of physical, chemical, radiological, or biological characteristics; (2) characterization and quantification of hazardous waste in the environment and their ecological effects; and (3) development, evaluation, and demonstration of environmental technology. General considerations about data requirements and application data for soil treatment may be found in US EPA documents at the following Internet sites: http://www.epa.gov/ada/pubs/issue.html and http://www.frtr.gov/matrix2/section1/toc.html.

**Natural Attenuation**

Natural attenuation is a passive remedial approach that depends upon natural processes to degrade and dissipate organic constituents in soil and groundwater.

Under appropriate site conditions, natural attenuation can reduce the potential impact of contaminated product release either by preventing constituents from being transported to sensitive receptors or by reducing constituent concentrations to less harmful levels. The policies and regulations of each area determine whether or not natural attenuation will be allowed as a treatment option.

The essential nutrients required for biodegradation usually are naturally present in the subsurface. Aerobic biodegradation consumes oxygen that, if not replenished, can limit the effectiveness of further aerobic biodegradation. Anaerobic biodegradation is also a significant attenuation process. Oxygen depletion in the subsurface is a characteristic of biodegradation of petroleum hydrocarbons and is a consequence of the rate of metabolic oxygen utilization exceeding the natural capacity for oxygen replenishment. The core of a contaminant plume typically is under anaerobic conditions and only the margins are aerobic. Therefore, even though the rate of anaerobic biodegradation is much slower than aerobic biodegradation (often by a factor of ten to several hundred), anaerobic processes may dominate the degradation of hydrocarbon contaminants. When oxygen is depleted, an alternative electron acceptor (e.g., NO$\text{}_3^-$, SO$\text{}_4^{2-}$, Fe$^{III}$) and a microorganism capable of using the alternative electron acceptor must be available for biodegradation to occur (US EPA, 2000). Physical processes such as volatilization, dispersion, and sorption also contribute to natural attenuation.
A detailed site investigation is necessary to provide sufficient data on site conditions and contaminant constituents present to evaluate the potential effectiveness of natural attenuation. In addition, site conditions will need to be monitored over time in order to confirm whether or not contaminants are being naturally degraded at reasonable rates to ensure protection of human health and the environment.

An extensive investment in site characterization and mathematical modeling often is necessary to establish the contribution of natural attenuation at a particular site. The natural Attenuation Decision Support System “BIOSCREEN” (EPA/600/R-96/087) is a computer program designed to simulate biodegradation by both aerobic and anaerobic reactions. Further innovative computer software tools, “Bioredox” and “SEQUENCE” at http://www.rovers.com, were developed to assist in the evaluation of natural attenuation conditions and to predict the performance of intrinsic or accelerated bioremediation remedies.

In Situ Biological Treatment for Soil

The main advantage of in situ treatment is that it allows soil to be treated without being excavated and transported, resulting in potentially significant cost savings. However, in situ treatment generally requires longer time periods, and there is less certainty about the uniformity of treatment because of the variability in soil and aquifer characteristics and because the efficacy of the process is more difficult to verify.

Bioremediation techniques are techniques directed toward stimulating the microorganisms to grow and use the contaminants as sources of nutrients and energy by creating a favorable environment for the microorganisms (Faber, 1997). Generally, this means providing some combination of oxygen, nutrients, and moisture, and controlling the temperature and pH. Sometimes, microorganisms adapted for degradation of the specific contaminants are added to enhance the process.

Biological processes typically are implemented at low cost. Contaminants can be destroyed, and often little to no residual treatment is required. However, the process requires more time, and it is difficult to determine whether or not contaminants have been destroyed. Although not all of the organic compounds are amenable to biodegradation, bioremediation techniques have been successfully used to remediate soils and groundwater contaminated by petroleum hydrocarbons, solvents, pesticides, wood preservatives, and other organic chemicals (Exxon, 1989). The specific contaminants present and their concentrations, oxygen supply, moisture, temperature, pH, nutrient supply, bioaugmentation, co-metabolism, and other soil parameters influence the rate at which microorganisms degrade contaminants (Atlas, 1984).

Treatability or feasibility studies are used to determine whether bioremediation would be effective in a given situation. The extent of the study can vary depending on the nature of the contaminants and the characteristics of the site. Available in situ biological treatment technologies include bioventing, enhanced biodegradation, landfarming, natural attenuation, and phytoremediation.

Ex Situ Biological Treatment of Soil

The main advantage of ex situ treatment is that it generally requires shorter time periods than in situ treatment, and there is more certainty about the uniformity of treatment
because of the ability to homogenize, screen, and continuously mix the soil. However, ex situ treatment requires excavation and transport of soils, leading to increased costs and engineering for equipment, and considerations associated with material handling/worker exposure.

Bioremediation techniques are destruction or transformation techniques directed toward stimulating the microorganisms to grow and use the contaminants as a food and energy source by creating a favorable environment for the microorganisms. Generally, this means providing some combination of oxygen, nutrients, and moisture, and controlling the temperature and pH (Civilini, 1994). Sometimes, microorganisms adapted for degradation of the specific contaminants are incorporated to enhance the process (Kosaric, 1993).

Biological processes are typically implemented at low cost. Contaminants can be destroyed or transformed, and little to no residual treatment is required. However, the process requires more time and it is difficult to determine whether or not contaminants have been destroyed.

Treatability or feasibility studies are used to determine whether or not bioremediation would be effective in a given situation. The extent of the study can vary depending on the nature of the contaminants and the characteristics of the site. For sites contaminated with common petroleum hydrocarbons, it is usually sufficient to examine representative samples for the presence and level of an indigenous population of microbes, nutrient levels, presence of microbial toxicants, and soil characteristics such as pH, porosity, and moisture.

Available ex situ biological treatment technologies include biopiles, composting, anaerobic digestion, genetically engineered organisms, landfarming, and slurry phase biological treatment.

In conclusion, with respect to hazardous waste treatment, composting offers a viable option because it is a versatile process at both physical and microbial levels. Its physical attributes are favorable for the one-time treatment of contaminated bulk wastes and soils, and the process can also be managed for routine waste treatment. The process is compact and, due to its solid-phase nature, it can be applied to both hydrophilic and hydrophobic wastes.

7.3. References

Quality and agronomic use of compost

and liquid agricultural wastes, P. L’Hermite, Commission of the European Communities, Brussels, Belgium, 212.


Appendix I.  Evaluation of Hazards to the Food Chain

Chemical Extractability

The problem of assessing the impact of the large amount of heavy metals present in various wastes on the natural equilibria of the soil is not easily solved due to the multitude of variables involved.

The waste materials themselves are very different in terms of their content of heavy metals and of the distribution of these metals in their various chemical forms. This high variability is related to the factors typical of the waste production process, origin of the wastes, and the type and level of treatment undergone.

The mobility of heavy metals in the soil is strongly determined by their chemical form in the waste materials. The heavy metals are subjected with time to the chemical reactions mentioned in the previous paragraph, assuming chemical forms, which have different availabilities to plants.

Thus, it is essential to be aware not only of the total concentration of the heavy metals (considered as a reserve controlling long-term behavior), but also of their distribution in the various chemical forms, especially those immediately soluble and exchangeable. Many chemical reagents are used to determine the available metals. The most utilized are: (1) simple aqueous solutions; (2) solutions of varying concentrations of alkaline and alkaline-earth metals; (3) complexing agents such as ethylene diamino tetracetic acid (EDTA), diethylene triamino pentaacetic acid (DTPA), nitrilo triacetic acid (NTA), which should also extract the metals complexed or adsorbed by organic substances; and (4) mixtures of the extractants mentioned above.

Water generally extracts small amounts of heavy metals and only the most refined analytical techniques manage to detect such low concentrations.

Neutral salts can extract metals bound to negative-charged soil surfaces. The amount of extractable metals in waste-treated soils range from less than 1% of the total to about 20%, particularly in the case of cadmium (Andersson, 1974).

The extraction of available metals by chelating agents allows the evaluation of those chemical forms bound to the organic fractions of the soils or of the wastes. The extractability of Cu, Zn, and Ni in fields treated with sludge generally is higher than in the untreated fields. The extractability of Zn and Cr in EDTA tends to increase by increasing pH, whereas Cu extractability is independent of pH. It has been reported that the addition of sludge significantly increases the quantity of Cd, Cu, Zn, and Ni extractable in DTPA (Street et al., 1977; Schauer et al., 1980).

Bioassay Experiments

Extractability can be considered as an index of the mobility of heavy metals. The extractable fraction represents the total amount of heavy metals present and sufficiently

---

1Literature cited is included in the reference section of this chapter.
mobile so as to be removed from the system by means of absorption by plants or washing out into the groundwater.

Plants mainly regulate the transfer of heavy metals from the soil to the food chain. It is therefore necessary to assess which part of the heavy metals present in the soil in a mobile form is effectively available for plant nutrition and is really absorbed.

This type of research is very complex since the quantity of metals absorbed essentially depends on the plant species considered and other particular characteristics such as the rapidity of growth, and the type of root system. Plants of the same species grown in different soils absorb different quantities of heavy metals and the same occurs when different species grow in the same soil.

In greenhouse or pot experiments, the plant itself is used as an extracting agent and the absorption of the metals is a direct index of their availability in the soil.

This type of bioassay is particularly useful to examine the effects caused by compost addition to soil.

In this way, allowances can be made for possible synergistic or antagonistic interactions among metals. For example, Zn and Cd are present in nature together, have analogous chemical characteristics, and often are found in many types of wastes. Their competition in the uptake process means that in the presence of high amounts of Zn, the Cd content of plants is relatively limited, with effective beneficial results from a biological point of view (Schauer et al., 1980).

Absorption, therefore, does not depend only on the concentration of the heavy metals, but also on their interactions, both in the soil and in the plant tissues.

In pot experiments, plants absorb greater amounts of heavy metals compared with field tests at the same levels of wastes used. This is mainly because in the bioassay tests the root biomass comes into contact only with the treated soil, whereas in the field the roots can extend beyond the area treated with the wastes.

To evaluate the transfer of heavy metals from soil to plant more thoroughly, two indices have been suggested: (1) the accumulation index, which is defined as the ratio between the concentration of the metal in the plant and the total concentration of the same metal in the soil; and (2) the transfer coefficient, which is defined as the ratio between the increase of concentration of a metal in the plant and the increase of the same metal in the soil.

Long-Term Effects

The scientific community currently is committed to predicting the possible effects of the use of biomass in agriculture in the long term. Given that the quality of the biomass produced today is being continually improved and the production of “quality biomass” is very recent, little is known about the long-term effects of this type of material on the soil.

Some mathematical models have been suggested to forecast long-term effects. The model proposed by Harmsen (1992) seems particularly useful in soil treated with compost. It is based essentially on an assessment of the following parameters:

- original content of heavy metals in the soil;
- amount of metals applied each year with compost;
• the plant species that determines the amount of metals removed with the harvest; and
• the amount lost due to leaching.

In the models used to describe the long-term behavior of metals, the variables should be considered as derivatives of time. Defining, for example, the amount of metals added to the soil as \( \frac{dq_i}{dt} \), the amount that accumulates in the arable layer \( \frac{dq_s}{dt} \), the amount removed by the plants \( \frac{dq_p}{dt} \), and that lost through leaching \( \frac{dq_l}{dt} \), for a given soil layer the following relation applies (Harmsen, 1992):

\[
\frac{dq_i}{dt} = \frac{dq_s}{dt} + \frac{dq_p}{dt} + \frac{dq_l}{dt}
\]  

(1)

All of these quantities are expressed as amount of metal per unit area per unit time, for example, kg ha\(^{-1}\) year\(^{-1}\). Assuming that the input of heavy metals starts from time “zero,” corresponding to the first application of compost, and that the amounts added in successive years remain constant, the following relation applies for \( t \geq 0 \):

\[
\frac{dq_i}{dt} = k_i
\]  

(2)

where \( k_i \) is a constant expressed in kg ha\(^{-1}\) year\(^{-1}\).

In order to distinguish between the original content of the soil, \( q_s(0) \), and that at time \( t \), \( q_s(t) \), we define the amount:

\[
\Delta q_s = q_s(t) - q_s(0)
\]

which represents the amount of metals that has accumulated in the soil.

Equation (1) thus becomes:

\[
\frac{d\Delta q_s}{dt} = k_i - \frac{dq_p}{dt} - \frac{dq_l}{dt}
\]  

(3)

From this general equation, it is possible to predict the behavior, in the long term, of the heavy metals added with compost in relation to the values of \( dq_p \) and \( dq_l \), which will depend on the solubility of the metals under different conditions.

Phenomena of accumulation in the soil occur only if:

\[
\frac{dq_p}{dt} + \frac{dq_l}{dt} < \frac{dq_i}{dt}
\]  

(4)

The solubility of the metals can be defined, in general terms, according to three possible cases:

(1) The solubility depends on the reactions of precipitation and solubilization. Therefore, it is not related to the amount of metals present in the solid phase of the soil.
In this case, we should not worry excessively about their potential increase in agricultural soils, because their bioavailability will not increase with time, and the amounts removed by the plants and by leaching will be constant, that is:

\[
\frac{dq_p}{dt} = k_p \quad \text{and} \quad \frac{dq_l}{dt} = k_l
\]

Equation (3) becomes:

\[
\frac{d\Delta q_s}{dt} = k_i - k_p - k_l
\]

(II) The solubility is regulated by the completely reversible phenomena of adsorption, of a linear or non-linear type.

The concentration of the metal in solution increases, more or less proportionately, with increasing adsorption of the metal on the solid phase. If the adsorption of a heavy metal from solution onto the solid phase of the soil is, for example, linear, it can be described by the expression:

\[
\Delta q_s = kC
\]

where \( k \) is a constant of adsorption and \( C \) is the concentration expressed in kg ha\(^{-1} \).

The following relations apply:

\[
\frac{dq_p}{dt} = k_p \Delta q_s \quad \text{and} \quad \frac{dq_l}{dt} = k_l \Delta q_s
\]

General Equation (3) becomes:

\[
\frac{\Delta q_s}{dt} = k_i - (k_p + k_l) \Delta q_s
\]

In this case, the amount of metals removed by plants or lost through leaching will tend to increase with time. As an extreme situation, all the metals added to the soil from a certain moment on could be involved in the environmental processes. However, this is a quasi-theoretical case, which could occur, for example, only in soil with very high acidity, given that metals in the soil undergo irreversible immobilization reactions, as described in the following case.

(III) Reversible and irreversible adsorption processes regulate the solubility.

This is the most common case and with the highest number of experimental verifications (Petruzzelli et al., 1989; Chaney and Ryan, 1993), in which parts of the metals added to the soil are irreversibly adsorbed. It is well known, in fact, that most of the processes of adsorption in the soil are not reversible and that the metals tend to bond with the reactive groups of the soil surfaces in an irreversible manner.
The following relation applies:
\[ \Delta q_s = \Delta q_{\text{rev}} + \Delta q_{\text{irr}} \]  

(7)

and the solubility of the metal is regulated only by \( \Delta q_{\text{rev}} \).

Assuming that the rapidity of transformation of the chemical forms is of the first order according to the equation:
\[ \frac{\Delta q_{\text{irr}}}{dt} = k_i \Delta q_{\text{rev}} \]  

(8)

where \( k_i \) is a constant of velocity (years\(^{-1}\)). From Equations (7) and (8), we have general Equation (9) as follows:
\[ \frac{\Delta q_{\text{rev}}}{dt} = k_i - \frac{dq_p}{dt} - \frac{dq_l}{dt} - k_i \Delta q_{\text{rev}} \]  

(9)

In this case, the amount in solution, and therefore available for plant nutrition and influenced by leaching and percolation processes toward the water table, depends exclusively on the chemical forms adsorbed reversibly and not by the total amount in the soil.

We must, however, take into account that the validity of these models is always limited. This is because the relation between biological availability and the solubility of heavy metals is extremely complex. It depends, moreover, on the competitive and synergistic effects existing between the various metals, on the plant species cultivated, on the distribution and density of the root system, on the structural properties of the soil, on the processes of release of chelating agents that occur in the rhizosphere, and also on the varying humidity and temperature during the growing season. It is clear that it is very difficult for models to take into account all of these specific parameters. However, choosing the right plants to use and the best type of compost to apply, models enable us to plan applications of quality products over several years and to assess, with a certain approximation, the accumulation of a metal with time, in a specific soil, so that any possible pollution can be avoided.

Conclusions

The soil has always been the final destination of wastes and it has always carried out its function of a natural system able to interact with wastes. In fact, soil organic matter derives from plant and animal residues introduced every year into the soil. Agricultural practices have always used residues such as manure and straw. Even if in this context the soil takes advantage of the interaction with residues, some wastes do not produce beneficial effects for the soil and can significantly lower the functions of protection that the soil carries out toward other environmental compartments. A suitable selection of the wastes can therefore notably reduce the potential risks deriving from heavy metals. To know the
distribution of the metals in the various types of wastes can help in prioritizing the actions to be undertaken in terms of waste sorting and source-separated collection. In this way, it is possible to obtain high-quality compost with a limited concentration of pollutants.

Since the amount of wastes is continuously growing, there is an urgent need to develop environmentally safe strategies for the utilization of biomass. It is evident that the characteristics of the soil will determine the amount of heavy metals accumulating after addition of biomass. However, to establish whether or not the soil has exceeded the thresholds of metal that can damage the food chain, the most critical soil parameter is not the total heavy metal content, but the amount of species that are mobile. This largely depends on the distribution of the metals between the liquid and the solid phases of the compost–soil system.

Compost can contribute to the retention of heavy metals for a long period. However, the contribution of compost to the process of metal retention depends strictly on the kind, the quality, and the amount of the compost added. In particular, since the sorption capacity is inversely related to the amount of metal sorbed, only “low metal” biomass will be able to provide new sorbing sites free of heavy metals in addition to the ones supplied by the soil. The production of compost for agricultural use should be aimed at materials of this quality.
Appendix II. Vermicomposts from Organic Waste

The first studies on earthworms date back to Charles Darwin (1881), who described the role of these segmented worms in the soil. He said that the plough was one of the oldest and most useful inventions made by man; but long before humanity ever existed, the soil had been tilled, and still is tilled, by earthworms. He then added that he doubted if any other animal had played such a major role in the history of the world as these low organisms.

Among the main functions cited by Darwin is the one, without delving too deeply into his treatise, that today we could call soil “digestion,” or even better pedologic substrate “digestion,” at least in the sense accepted by the naturalist. According to Darwin, the dark color and fine texture of “vegetal soil” are mainly the result of the action of earthworms.

All materials digested by the earthworms’ intestines show enhanced agricultural properties (fine texture, more easily attacked by bacteria, fungi, and actinomycetes). Furthermore, another point that Darwin could not even have imagined, is that earthworms enrich the material they digest with substances that are commonly called growth regulators. In fact, it has been seen that the application of soil amendment products digested by earthworms enriches microbial metabolites that, in turn, stimulate vegetal crop yield. Data in the literature report on the hormone-like effects of matter digested by earthworms on crops, and detectable amounts of auxins, gibberelin, and cytokines have been revealed.

Although it was known that earthworms enhanced soil fertility, studies on the so-called “earthworm castings” were initiated only in the 1940s in Germany and revealed the importance of the castings for soil germination and root development of many agricultural species. A review of the literature showed that most studies focus on the action of earthworms on soil, whose positive effects on chemical, physical, and biological fertility have been known for a long time (Berley, 1961; Ehlers, 1975; Hartestein and Mitchell, 1978; Ash and Lee, 1980; Syers and Springett, 1984).

Nonetheless, there are very few studies on vermicomposts or castings (the name given to bioconversion products) that are the result of the action of earthworms on organic waste (Nardi et al., 1983; Riffaldi and Levi-Minzi, 1983; Bouché, 1987).

Vermicomposting is the process of preparing compost from organic waste with the help of earthworms, the most important of all the large decomposers. The worms consume bacteria, fungi, protozoa, and organic matter. As the worms digest organic material, they leave nutrient-rich castings in their path. Unlike other decomposers, they break down material, both physically and chemically.

It has been observed by several researchers that earthworm castings usually contain more total and nitrate nitrogen, organic matter, total and exchangeable magnesium, available phosphorus, base capacity, and moisture equivalent (Lee, 1985). This fact should hold true whether the surrounding environment be soil, manure, or other. Not only is it possible to compost faster and with more nutrients than regular compost, but the physical

---

2Literature cited is included in the list of references for this chapter.
structure of the soil and its biological properties (enrichment of microorganisms, addition of growth hormones such as auxins and gibberelic acid, addition of enzymes, etc.) can be ameliorated. All of these improvements — increased plant nutrient availability, better water-holding capacity, better water infiltration, soil erosion control, improved aeration, improved organic carbon content, etc. — dramatically enhance soil health and fertility.

The main characteristics of castings are presented in Table 7.5.

Usually the producers of vermicompost market a wide range of products that vary considerably in characteristics and performance, and this reflects the great diversity of organics and mixtures that are being processed and the degree of processing. Many vermicompost producers have marketing problems and these are usually related to product variability. Although many producers claim to have tested their products for plant growing, in many cases these tests were not conducted adhering to strictly scientific methods with controls and replicates. Moreover, the results sometimes are difficult to interpret.

Table 7.5. Main characteristics of castings and respective matrices (values referred to dry matter 105°C)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ash (%)</th>
<th>pH</th>
<th>Organic C (%)</th>
<th>Total N (Kjeldal) (%)</th>
<th>C/N</th>
<th>Organic matter (from ashes) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle manure</td>
<td>33.60</td>
<td>8.90</td>
<td>28.20</td>
<td>2.46</td>
<td>11.50</td>
<td>66.40</td>
</tr>
<tr>
<td>Cattle casting</td>
<td>64.90</td>
<td>6.40</td>
<td>18.40</td>
<td>1.87</td>
<td>9.80</td>
<td>35.10</td>
</tr>
<tr>
<td>Pig manure</td>
<td>11.70</td>
<td>6.60</td>
<td>43.10</td>
<td>3.06</td>
<td>14.10</td>
<td>88.30</td>
</tr>
<tr>
<td>Pig casting</td>
<td>31.30</td>
<td>5.80</td>
<td>33.80</td>
<td>2.96</td>
<td>12.60</td>
<td>68.30</td>
</tr>
<tr>
<td>Sheep manure</td>
<td>34.90</td>
<td>8.80</td>
<td>31.30</td>
<td>3.11</td>
<td>10.10</td>
<td>65.10</td>
</tr>
<tr>
<td>Sheep casting</td>
<td>44.20</td>
<td>8.60</td>
<td>29.00</td>
<td>3.07</td>
<td>9.40</td>
<td>55.80</td>
</tr>
<tr>
<td>Mixed manure A</td>
<td>21.60</td>
<td>8.50</td>
<td>38.10</td>
<td>1.83</td>
<td>20.80</td>
<td>78.40</td>
</tr>
<tr>
<td>Mixed manure A casting</td>
<td>53.30</td>
<td>7.50</td>
<td>23.80</td>
<td>2.26</td>
<td>10.50</td>
<td>46.70</td>
</tr>
<tr>
<td>Mixed manure B</td>
<td>74.30</td>
<td>8.50</td>
<td>11.40</td>
<td>1.21</td>
<td>9.40</td>
<td>25.70</td>
</tr>
<tr>
<td>Mixed manure B casting</td>
<td>75.10</td>
<td>6.60</td>
<td>11.30</td>
<td>1.03</td>
<td>10.90</td>
<td>24.90</td>
</tr>
<tr>
<td>Cattle manure + cardboard*</td>
<td>26.50</td>
<td>8.10</td>
<td>32.90</td>
<td>1.98</td>
<td>16.60</td>
<td>73.50</td>
</tr>
<tr>
<td>Cattle manure casting + cardboard*</td>
<td>65.20</td>
<td>7.60</td>
<td>15.80</td>
<td>1.53</td>
<td>10.40</td>
<td>34.80</td>
</tr>
<tr>
<td>Poultry manure + cellulose**</td>
<td>42.00</td>
<td>9.00</td>
<td>24.30</td>
<td>2.82</td>
<td>8.60</td>
<td>58.00</td>
</tr>
<tr>
<td>Poultry manure casting + cellulose</td>
<td>63.30</td>
<td>8.50</td>
<td>17.30</td>
<td>1.66</td>
<td>10.40</td>
<td>36.70</td>
</tr>
</tbody>
</table>

A — 70% cattle organic waste + 30% pig organic waste.
B — 20% horse manure + 30% pig manure + 30% cattle manure + 20% poultry manure.
*50% cattle manure + 50% paper.
**50% poultry manure + 5% cellulose.
Even if the technology for processing organic wastes by vermiculture has evolved from ground beds to advanced technology systems, many worm growers still are using relatively inefficient methods to produce their vermicomposts. Methodologies range from these obsolete methods, to improved wedge systems of vermicompost production, and finally to advanced technological systems with completely automated continuous flow reactors, each capable of processing more than 1000 tons of waste per year. Australia, New Zealand, and the USA are pioneering these new developments.

Use of different organic waste types as ingredients for vermicomposts needs the correct selection of specific microbiota to increase the value of the final product. The properties of worm composts are markedly affected by bacteria.

It is well known that Gram-negative bacteria are common inhabitants of the intestinal canal of soil animals, including earthworms. However, little is known about their taxonomic positions at genus or species level (Brown, 1995; Masciandaro et al., 2000; Toyota and Kimura, 2000).

Verkhovtseva et al. (2000) studied the composition of microbial communities of the worm composts after preparation of sewage sludge and cattle manure vermicomposting (via Eisenia fetida culture), both qualitatively and quantitatively.

Examples of innovation and process improvements can be found in the USA. For example, changes in soil biochemical, physical, and microbiological properties during the processing of separated hog manure by earthworms and for food waste processing in a continuous flow reactor system have been analyzed. An automated large-scale vermicomposting machine was developed. The modular system works as a series of stacked conveyor belts for worm beds. Manure, food, residuals, biosolids, or other feedstocks are placed in a hopper above the feeder. The stackable design allows beds to be placed both vertically and horizontally to fill a desired space.

Besides many factors that have limited the expansion of vermicomposts within the EU have been the scarce interest in biological products (something that has drastically changed in recent years), vermicompost producers’ reluctance to invest in research and new technologies (due to moderate market activity), and the lack of quality standards for their products, which has made it difficult to develop consistent marketing and product differentiation strategies.

Agronomic Effectiveness

Experiments have been conducted to assess the agronomic effectiveness of earthworm castings and the efficacy of the bioconversion process. Characterization of the chemical type of the original product with respect to the final product has revealed the following features for organic waste vermicomposts:

1. marked reduction in organic matter that is mainly due to the loss of organic carbon,
2. limited reduction in total nitrogen,
3. relevant increase in assimilable nitrogen, particularly nitric nitrogen, mainly in pig castings where nitrogen content reaches 0.3%,
4. reduction in the C/N leading to improved organic matter quality, especially in pig and cattle castings,
5. constant decrease in pH that may be caused by the production of organic acids and microbial metabolism CO₂,
6. increased cation exchange capacity, a clear example of enhanced product humification; and
7. mineral elements, in particular phosphorus, copper, and zinc, do not show the same pattern because of two concomitant factors: on one hand their concentrations increase because inorganic matter decreases, while on the other they decline because they are absorbed by earthworms.

Available and total nutrients in castings and their prospective matrices are shown in Table 7.6.

Increased humification rate has been observed, even if this result, to some extent, depends on the loss of organic matter occurring during bioconversion. The increase in the

Table 7.6. Available and total nutrient in casting and respective matrices (values referred to dry matter 105°C)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mineral N mg kg⁻¹</th>
<th>Total P (%)</th>
<th>Organic P (%)</th>
<th>Available P₂O₅ mg kg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N–NH₄</td>
<td>N(NO₃ + NH₄)</td>
<td>N–NO₃/N–NH₄</td>
<td></td>
</tr>
<tr>
<td>Cattle manure</td>
<td>7</td>
<td>541</td>
<td>76</td>
<td>0.71</td>
</tr>
<tr>
<td>Cattle casting</td>
<td>9</td>
<td>1991</td>
<td>220</td>
<td>0.75</td>
</tr>
<tr>
<td>Pig manure</td>
<td>162</td>
<td>207</td>
<td>0.28</td>
<td>0.76</td>
</tr>
<tr>
<td>Pig casting</td>
<td>78</td>
<td>2997</td>
<td>37</td>
<td>0.43</td>
</tr>
<tr>
<td>Sheep manure</td>
<td>11</td>
<td>2622</td>
<td>237</td>
<td>0.69</td>
</tr>
<tr>
<td>Sheep casting</td>
<td>18</td>
<td>2163</td>
<td>119</td>
<td>0.22</td>
</tr>
<tr>
<td>Mixed manure A</td>
<td>138</td>
<td>175</td>
<td>0.27</td>
<td>0.54</td>
</tr>
<tr>
<td>Mixed manure A casting</td>
<td>20</td>
<td>2556</td>
<td>127</td>
<td>1.03</td>
</tr>
<tr>
<td>Mixed manure B</td>
<td>10</td>
<td>1346</td>
<td>134</td>
<td>0.38</td>
</tr>
<tr>
<td>Mixed manure B casting</td>
<td>20</td>
<td>1715</td>
<td>85</td>
<td>0.46</td>
</tr>
<tr>
<td>Cattle manure + cardboard*</td>
<td>155</td>
<td>836</td>
<td>7</td>
<td>0.59</td>
</tr>
<tr>
<td>Cattle manure casting + cardboard*</td>
<td>111</td>
<td>776</td>
<td>6</td>
<td>0.76</td>
</tr>
<tr>
<td>Poultry manure + cellulose**</td>
<td>25</td>
<td>56</td>
<td>1</td>
<td>1.97</td>
</tr>
<tr>
<td>Poultry manure casting + cellulose</td>
<td>19</td>
<td>782</td>
<td>40</td>
<td>0.59</td>
</tr>
</tbody>
</table>

A — 70% cattle organic waste + 30% pig organic waste.
B — 20% horse manure + 30% pig manure + 30% cattle manure + 20% poultry manure.
*50% cattle manure + 50% paper.
**50% poultry manure + 50% cellulose.
Compost science and technology

degree of humification is more important. Therefore, bioconversion primarily enriches the nitrogen content of the humic fraction, more than an increase in humification.

Very few real and proper agronomic trials have been carried out. Investigations on earthworm castings mainly focus on the efficacy of the composting processes and very often have been restricted to revealing the differences between original matrices and end products. Some trials have been conducted on young pot-grown laboratory plants at the initial stages of development, whereas very few field trials have been performed.

A noteworthy trial was carried out to assess the possible environmental impact caused by application of a great amount of pig slurries, either as primary matrix or composted by bioconversion using *Eisenia fetida*, to fertilize industrial crops, such as corn or sorghum. In particular, the agronomic trials compared results obtained using cattle and pig castings with their respective matrices, with and without mineral fertilization. The findings revealed that castings from cattle manure gave higher yields than observed using organic waste that was not transformed by earthworms. Furthermore, pig slurries reduced yields as the primary matrix, whereas castings from pig manure produced markedly higher yields than those observed in the untreated soil. Mineral fertilizer amendment increased crop yield achieved using cattle manure and decreased the reduction caused by pig manure (see Table 7.7). Application rates of 50–100 tons ha\(^{-1}\) are typical for cattle manure treatments, at least in livestock farming areas. However, in other sectors of agriculture, the high production costs of vermicasting from bioconversion of manure mean that such elevated doses are viable only for small areas or greenhouses growing high profit market garden, nursery garden, or other specialized plants.

Studies reported in the literature to date have shown that manure bioconversion by *Eisenia fetida* neither reduced organic matter nor enhanced its quality. In some cases,

---

### Table 7.7. Production expressed in q/ha of dry matter of sweet sorghum grown under different cropping conditions

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Without mineral fertilization</th>
<th>With mineral fertilization*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>100b</td>
<td>125b</td>
</tr>
<tr>
<td>50 tons ha(^{-1}) cattle manure</td>
<td>152c</td>
<td>178cd</td>
</tr>
<tr>
<td>50 tons ha(^{-1}) cattle casting</td>
<td>183cd</td>
<td>221d</td>
</tr>
<tr>
<td>100 tons ha(^{-1}) cattle manure</td>
<td>169c</td>
<td>220d</td>
</tr>
<tr>
<td>100 tons ha(^{-1}) cattle casting</td>
<td>222d</td>
<td>304e</td>
</tr>
<tr>
<td>50 tons ha(^{-1}) pig slurry</td>
<td>51a</td>
<td>78a</td>
</tr>
<tr>
<td>50 tons ha(^{-1}) pig casting</td>
<td>141bc</td>
<td>184cd</td>
</tr>
<tr>
<td>100 tons ha(^{-1}) pig manure</td>
<td>36a</td>
<td>45a</td>
</tr>
<tr>
<td>100 tons ha(^{-1}) pig casting</td>
<td>179cd</td>
<td>181cd</td>
</tr>
</tbody>
</table>

Values followed by different letters present significant statistical differences \((P = 0.05)\).

\(^{a}\)q/ha = 100 kg/ha.

\(^{*}\)(NH\(_4\))\(_2\)PO\(_4\) in doses of 0.5 tons ha\(^{-1}\).

the humification process increased the nitrogen content of humic acids closely related to their physiological activity.

Our overall data set clearly demonstrates that pig slurries are most suitable for bioconversion. This datum is of major importance since the well-known pollution problems caused by pig farming can be reduced, as can the negative environmental impact of manure treatments.

Composting improves the texture of the product and thus makes it easier to commercialize on the market and distribute throughout the territory. Nevertheless, the main issue to be resolved still is to extend bioconversion procedures to substrates other than manure that has its own precise agronomic collocation.