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THE BIOLOGY OF COMPOSTING: A REVIEW

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This paper analyses the more important aspects of this process with particular emphasis on the microbiological. Some attention is also given to hygienic and sanitary implications as well as considerations on plant design. Compost is also analysed in its agricultural role, in particular its effects on plant growth. Problems regarding the evaluation of biological maturity and phytotoxicity are also discussed.

Key Words:—Solid urban waste, sewage sludge, composting, microbial ecology, organic fertilizer, land utilization, compost maturity, phytotoxicity, recycling, waste disposal.

1. Introduction

Landfill and incineration have until now been the most widely used means of solid waste disposal throughout the world, but in recent years interest has grown in disposal methods which take recycling into consideration. One of the more successful systems used in many countries is the transformation of biodegradable organic material from various sources into humic substances (Wiles 1978; Bewick 1980; Golueke 1977).

This paper is a detailed review of transformation processes of the organic fraction of solid urban waste into compost including processes used when the waste is mixed with sewage sludge.

Agricultural implications of the use of this form of organic fertilizer are discussed as well as those physical, chemical and microbiological parameters which are characteristic of composting.

2. Why composting?

Addition of fresh organic matter to the soil is to be avoided because it results in a change in the ecosystem in which the crop is developing (Kononova *et al.* 1966). Once the organic matter is placed in the soil, if it is not partially humified, it will be degraded by the microflora resulting in a production of intermediate metabolites which are not compatible with normal plant growth (Zucconi *et al.* 1981*a, b*). Other disadvantages are competition for nitrogen between micro-organisms and roots, a high carbon/nitrogen ratio (C/N), and the production of ammonia in the soil (Golueke 1977).

Composting is therefore a way of obtaining a stable product from biological oxidative transformation, similar to that which naturally occurs in the soil.

3. Microbial ecology of composting

Since composting is mainly a microbial process, knowledge of the various microbial

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TABLE 1
Composition of representative municipal solid waste

Item	Percentage
Organic (biodegradable)	47–60
Metals	6–8
Glass	4–8
Plastics	4–6
Other inorganic	10–13
Moisture	25–30

TABLE 2
Organic fraction composition of municipal solid waste

Item	Percentage
Volatile matter	70–90
Protein	2–8
Lipids	5–10
Total sugar	5
Cellulose	35–55
Starch	2–8
Lignin	3–8
Phosphorus	0.4–0.7
Potassium	0.7–1.7
Crude fibre	35–40

groups and their role in the process of bio-oxidation is essential. Composting passes through several stages, each of which is characterized by the activity of different microbial groups (Gray *et al.* 1971; Gray & Biddlestone 1973, 1974; Finstein & Morris 1975; de Bertoldi *et al.* 1979; de Bertoldi & Zucconi 1980).

Chemical composition of solid urban waste and its biodegradable fraction is heterogeneous (see Tables 1 & 2). Transformation through composting results in the mineralization and partial humification of the substances present.

3.1. *Carbon cycle*

Simple carbon compounds (soluble sugars, organic acids, etc.) are easily metabolized and mineralized by a heterotrophic and heterogeneous microflora. High metabolic activity and exothermic processes increase the temperature in the composting mass. This has a strong selective effect in favour of a few aerobic sporigenous thermophilic organisms.

Natural long chain polymers are attacked later principally by other microbial groups (fungi and actinomycetes). Several genera and species of eumycetes, mesophilic and thermophilic organisms actively degrade cellulose, pectin, starch and lignin (Table 3) (de Bertoldi & Zucconi 1980). Cellulose decomposition is intense throughout the process, but particularly during the final stages mostly through activity of eumycetes. In the later phases of composting we observed a continuous decrease in the number of cellulolytic bacteria and an increase in the number of cellulolytic eumycetes (Fig.

TABLE 3

Fungi isolated during composting of the organic fraction of urban solid waste (60%) mixed with sewage sludge (40%). Thermophilic strains were isolated at 50°C, mesophilic at 28°C; all strains were characterized according to their enzymatic activity: cellulolytic, pectinolytic, amilolytic and ligninolytic

Thermophilic	
Absidia ramosa	*Humicola lanuginosa*
Allescheria terrestris	*Lenzites* sp.
Mucor pusillus	*Penicillium duponti*
Chaetomium thermophilum	*Scytalidium thermophilum*
Talaromyces thermophilis	*Sporotrichum thermophile*
Aspergillus fumigatus	*Thermoascus aurantiacus*
Humicola insolens	*Micelia sterilia*

Mesophilic	Cellulolytic	Pectinolytic	Amilolytic	Ligninolytic
Ascomycotina				
Allescheria terrestris	+			+
Chaetomium sp.	+			
Dasyscipha sp.				+
Emericella nidulans			+	
Mollisia sp.				+
Thermoascus aurantiacus	+			+
Basidiomycotina				
Armillaria mellea	+			+
Clitopilus insitus	+			+
Coprinus cinereus	+			+
Fomes sp.	+			+
Lentinus lepideus				+
Lenzites trabea	+			+
Pleurotus ostreatus	+			+
Polyporus versicolor	+			+
Deuteromycotina				
Alternaria tenuis	+			
Artrobotrys oligospora	+			
Aspergillus amstelodami	+			
Aspergillus sp.	+			
Botryotrichum piluliferum	+			
Cephaliophora tropica	+			
Cephalosporiopsis alpina	+			
Cephalosporium sp. 1	+	+	+	
Cephalosporium sp. 2	+	+	+	
Cephalosporium sp. 3	+			
Cephalosporium sp. 4	+			
Cladosporium herbarum	+		+	
Dorathomyces sp.	+			
Geotrichum candidum	+		+	
Gliocladium sp.				+
Gliomastox murorum	+		+	
Graphium sp.			+	
Harpographium sp.			+	
Leptographium lundbergii	+		+	
Paecilomyces sp.	+			

	Cellulolytic	Pectinolytic	Amilolytic	Ligninolytic
Penicillium sp. 1	+			
Penicillium sp. 2	+		+	
Phlyctaena sp.			+	
Rhinocladiella artrovirens	+			
Scopulariopsis brevicaulis	+			
Scopulariopsis sp.	+			
Sporotrichum thermophile	+			+
Stachybotrys sp.	+	+	+	
Trichoderma viride	+		+	

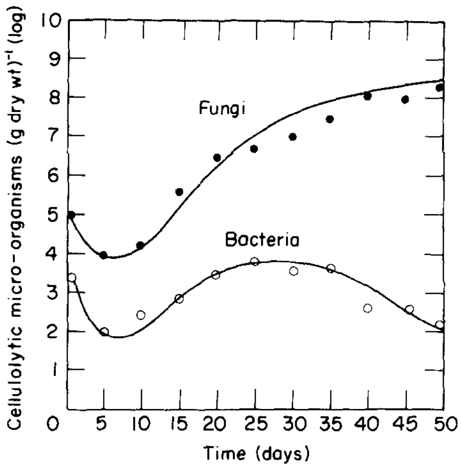

Fig. 1. Growth of cellulolytic bacteria and fungi during composting of the organic fraction of solid urban waste (60%) mixed with sewage sludge (40%). Static pile system with forced ventilation was used (de Bertoldi & Zucconi 1980).

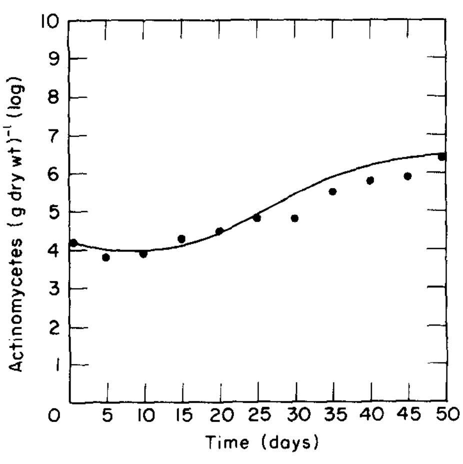

Fig. 2. Growth of actinomycetes during composting (conditions as in Fig. 1).

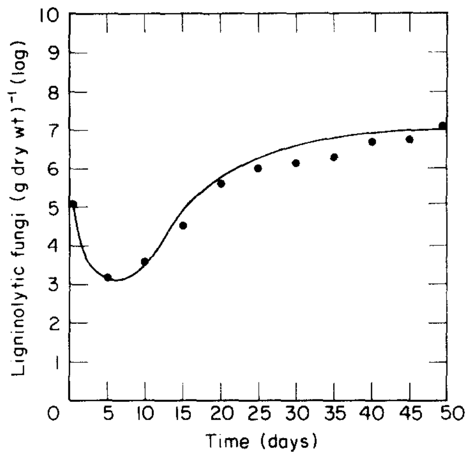

Fig. 3. Growth of ligninolytic fungi during composting (conditions as in Fig. 1).

1). The fungi benefit from the decrease in temperature, pH and moisture content that take place as the process evolves. The same three environmental factors positively effect the presence and diffusion of actinomycetes (Fig. 2). They become particularly abundant only in the last stages of decomposition. The metabolic activity of the actinomycetes is fundamental to the humification of organic matter and to the production of aromatic compounds (i.e. geosmin).

The degradation of lignin, an enzymatic aerobic transformation, is restricted to a limited microbial group, namely the higher fungi (basidiomycetes) (Table 3 & Fig. 3). Basidiomycetes degrade lignin slowly and do not reach their highest degree of activity until about 1 month after the starting of the compost process (Fig. 3). Lignin decomposition seems to be enhanced in the static pile composting system (with forced ventilation). Probably periodic turning disturbs the diffusion of hyphae into the mass and thereby interferes with the growth of basidiomycetes (de Bertoldi *et al.* 1982*c*).

3.2. *Nitrogen balance*

The nitrogen content usually decreases during the process of composting mostly through ammonia volatilization. This nitrogen loss can be evaluated in terms of absolute value. In terms of dry weight, on the other hand, there is an increase due to the mineralization of organic matter and consequent loss of CO_2 and H_2O, so that a decrease in the C/N ratio can be observed throughout the process (de Bertoldi *et al.* 1982*c*).

In spite of N loss through volatilization of ammonia, a partial recovery later takes place, due to the activity of nitrogen-fixing bacteria. Many species of these bacteria have been isolated during composting mostly in association with the mesophilic phases of the process (Table 4). Biological nitrogen fixation is inhibited by the presence of ammonia and by high temperatures (de Bertoldi *et al.* 1982*c*). Therefore nitrogenasic activity is higher during the later phases of decomposition.

Regardless of the composting system used, autotrophic nitrification appears to be absent in the earlier phases of the process. This type of nitrification was not detected until the completion of 20 days of composting. The inhibition of ammonium oxidation was not determined by the presence of soluble organic matter *per se* (Alexander 1977). Nitrification is markedly affected by temperature. Many investigations have confirmed

TABLE 4
N-Fixing bacteria isolated from composting solid urban waste

Aerobes	Growth at 37°C, not spore forming, ovoid cells, gram negative: *Azomonas*
Facultative aerobes	Growth at 37°C, not spore forming: *Enterobacter, Klebsiella*
	Growth at 50°C, endospore forming, gram positive and negative: *Bacillus*
Anaerobes	Growth at 40°C, sporigenous, rod-shaped, gram positive: *Clostridium*

the fact that, above 40°C, the rate of nitrification is very low (Alexander 1977). Excessive amounts of ammonia also inhibit the growth of nitrifiers, especially the nitricant ones (*Nitrobacter*) (Loehr 1974; Focht & Chang 1975).

Heterotrophic nitrification operated by other bacteria and eumycetes seems less subjected to conditioning by these factors. In fact, production of nitrate in the early phases of composting seems almost exclusively the work of heterotrophic-nitrifiers (Eylar & Schmidt 1959; Hora & Iyengar 1960; Hirsch *et al.* 1961; Marshall & Alexander 1962; Alexander 1977). Unfortunately rigorous methods of analyses are still not available which verify this statement conclusively.

Any inhibition of nitrification in the composting material may adversely influence the nitrogen balance and microbial activity during composting. Although ammonium is continuously produced by the degradation of nitrogen-containing organic molecules by innumerable micro-organisms, its biological oxidation to nitrate scarcely occurs in composting (de Bertoldi *et al.* 1982*c*).

4. Factors which influence composting

Composting is a spontaneous process in nature, such as in the breakdown of leaf litter or the forest floor and the ageing of cow manure. But the length of time and modalities of natural composting are long and heterogeneous and in any case unsuitable for industrial use.

The principal factors that contribute to making an optimum environment for the microbial processes in composting, and which can be made to be functions of technology are the following.

4.1. *Oxygenation*

Since composting is a biological oxidation, availability of oxygen during the process is of primary importance. Oxygen is used by micro-organisms as a terminal electron acceptor for aerobic respiration and also in the oxidation of several sorts of organic substances in the mass.

A function of aeration of the mass is to supply O_2 so that it does not become a limiting factor. Oxygen content in the circulating air should not fall below about 18%. Since this value must be constantly maintained, periodic aeration such as turning the piles is insufficient (de Bertoldi *et al.* 1982*c*). Only through continuous turning is constant oxidation guaranteed but this would raise running costs excessively and would interfere with the growth of some micro-organisms such as filamentous fungi.

Continuous forced ventilation through the mass maintains a satisfactory oxygen level. This ventilation may be through blowing or vacuum induced. Experimental research has demonstrated that blowing gives better control over both temperature and moisture (Suler & Finstein 1977; Finstein 1980; Finstein *et al.* 1980*a*, *b*; MacGregor *et al.* 1981; de Bertoldi *et al.* 1982*c*). This means that composting with blowing is quicker and gives a higher quality end-product than processes using vacuum induced ventilation (Epstein *et al.* 1976; Willson *et al.* 1976, 1980; Eralp 1981).

There is a relation between temperature and microbial oxygen consumption during composting. Temperatures between 30 and 55°C enhance microbial activity (Haug 1979; Finstein *et al.* 1980*a*). At this temperature, the highest oxygen consumption through microbial activity occurs.

4.2. *Temperature*

Too often, high temperatures have been considered a necessary condition for good composting. High temperatures are consequences of biological activity: heat, liberated through respiration of micro-organisms decomposing organic matter, builds up within the pile since dispersion is low due to natural insulation of solid urban waste (Finstein & Morris 1975). From the ecological point of view, Finstein calls this process "microbial suicide" (Finstein *et al.* 1980*a*). Excessively high temperatures in fact inhibit growth in the majority of micro-organisms present, thus slowing down decomposition of organic matter. Only a few species of thermophilic sporigenous bacteria show metabolic activity above 70°C: *Bacillus stearothermophilus*, *Bacillus subtilis*, *Clostridium* sp., and non-spore forming bacteria, gram-negative, aerobic: genus *Thermus* (Brock & Freeze 1969; Finstein & Morris 1975; Tansey & Brock 1978).

For rapid composting high temperatures for long periods must be avoided. An initial thermophilic phase may be useful in controlling thermosensible pathogens (Golueke 1982*b*). After this stage it is preferable to reduce temperatures to levels which allow development of eumycetes and actinomycetes which are the main decomposers of the long-chain polymers, cellulose and lignin (Chang 1967; Chang & Hudson 1967; Dunlap & Chiang 1980; de Bertoldi *et al.* 1982*c*). Optimal temperatures vary from 45 to 55°C.

The problem of temperature control is solved by using forced pressure ventilation throughout the process. The primary advantage of forced pressure ventilation is that it induces evaporative cooling in the region of the pile that is most highly insulated and carries heat to the outer layers. Another important feature in controlling temperature is the use of a temperature controlling unit responding to a temperature sensor placed in the pile. A ceiling temperature (45–50°C) is established in which blow time is automatically regulated by heat output, which is of course a function of biological activity (Finstein *et al.* 1980*a*, *b*; de Bertoldi *et al.* 1982*c*). Forced pressure ventilation in conjunction with temperature feed-back control seems to be the system which provides best temperature control and ensures continuity of the decomposition process, it facilitates water removal and permits a predictable composting rate (de Bertoldi *et al.* 1982*c*).

4.3. *Moisture*

Moisture content and aeration are closely interrelated in terms of displacement of air in the interstices by water and promotion of clumping and lowering of the structural strength of the material (Golueke 1982*a*). Optimal moisture content in composting varies and essentially depends on the physical state and size of the particles.

Modification in moisture during composting is complicated and expensive, making it important to have optimal values from the outset. Low values mean early dehydration of the pile which arrests the biological process giving a physically stable but biologically unstable compost. High quantities interfere with the aeration by clogging the pores.

When composting the organic fraction of solid urban waste sorted through biological and mechanical means, initial moisture content may be too low, particularly if air separation has been used. In this case the organic fraction can be mixed with sludge until moisture content reaches 65–67% (de Bertoldi *et al.* 1980; Golueke *et al.* 1980). This quantity will fall to below 30% within a month if composting is correctly carried out.

4.4. *Carbon/nitrogen ratio*

Low C/N ratios will slow decomposition and increase nitrogen loss. If the initial C/N ratio is greater than 35, the micro-organisms must go through many life-cycles, oxidizing off the excess carbon until a more convenient C/N ratio for their metabolism is reached; the C/N ratio of the micro-organism cells is about 10 and this theoretically would be the best value for their metabolism. In spite of that, this low value would lead to a nitrogen loss through ammonia volatilization especially at high pH and temperature values. After extensive experiments on composting of municipal solid waste (mixed and unmixed with sludge) it was determined that the general optimum C/N ratio was 25 in the starting material; higher values slowed the rate of decomposition, lower ones resulted in nitrogen loss. Since most organic residues (see Table 5) have a high C/N ratio, it is possible to correct it to favour good composting. This correction may take the form of adding sludge if available.

4.5. *pH level*

It is generally true to say that matter with a high range of pH (from 3 to 11) can be composted. However, optimum values are between 5.5 and 8. Whereas bacteria prefer a nearly neutral pH, fungi develop better in a fairly acid environment.

In practice it is not very easy to change the pH level in a pile. Generally, the pH begins to drop at the initiation of the composting process. This is a consequence of the activity of acid-forming bacteria which break down complex carbonaceous material to organic acid intermediates.

High values of pH in the initial phases of the process in association with high temperatures can cause a loss of nitrogen through volatilization of ammonia.

4.6. *Conditioning of starting material*

For rapid composting on an industrial scale organic material must undergo size reduction. The primary purpose of this operation is to increase the surface area of the material, inasmuch as the smaller the particle, the greater is the ratio of the surface area to mass. The speed of biological oxidation is in direct proportion to the amount of surface exposed to the reactive agent. While theoretically it may be true that the smaller the particle size, the better is the biological degradation, in practice limits exist to the size reduction which are a function of the structural strength of the raw material.

It is essential that material must be reduced in size but conserve sufficient interstices for the circulation of air. A solid substance keeps its shape when moist even when

TABLE 5
Carbon to nitrogen ratios of micro-organisms and some organic residues

Item	C/N
Micro-organisms	9–12
Raw sewage sludge	7–12
Activated sludge	6–8
Cow manure	17–19
Organic fraction of solid urban waste	26–45
Maize residue	80–90
Straw, wheat	120–150
Fresh sawdust	500–520

finely chopped, whereas a soft substance tends to be squashed.

In already existing solid urban waste treatment plants, preparation of the organic fraction for composting is carried out in two different ways: (a), mechanical; (b), biological-mechanical. Mechanical processes sort out inert material after shredding, hammer-mill size reduction, and screening; electromagnetic separation of metals, ballistic or aerated separation follow.

In biological-mechanical processes solid urban waste is placed in biological reactors for short periods (1–3 days) during which they undergo an initial biological transformation together with size reduction. At this stage the biodegradable organic fraction has been drastically conditioned and disintegrated and is therefore more easily separated by mechanical means from inert material.

5. Practical systems of composting

There is still much confusion today over the meaning of the word compost. Composting is a microbial reaction of mineralization and partial humification of organic substances which under optimum conditions take place within a month. It is very difficult to decrease this time and it is not possible for composting to take place in a few days as many assert. Composting time depends on the biological cycles of the micro-organisms involved. Replication time is conditioned by environmental factors and genetical constitution of the micro-organisms. Although environmental factors may be improved, genetic limits remain.

Transformation into compost can take place either in closed reactors or in windrows in the open. If the processes are correctly carried out, there is no difference in the maturation time. Closed systems have the advantage of offering greater controllability than open-air systems. They do have, however, higher initial and running costs.

The most common methods are the open windrow systems because they are more versatile and give more highly predictable results (USEPA 1971, 1975; Epstein 1977; Smith 1978; Golueke 1978, Goldstein 1980; Gunn 1980; Coker & Murray 1981; Haug & Davis 1981; Higgins 1982; Jongejan 1982; Kresse 1982).

6. Evaluation of compost maturity

At present, compost maturity evaluation is a problem which requires further and better

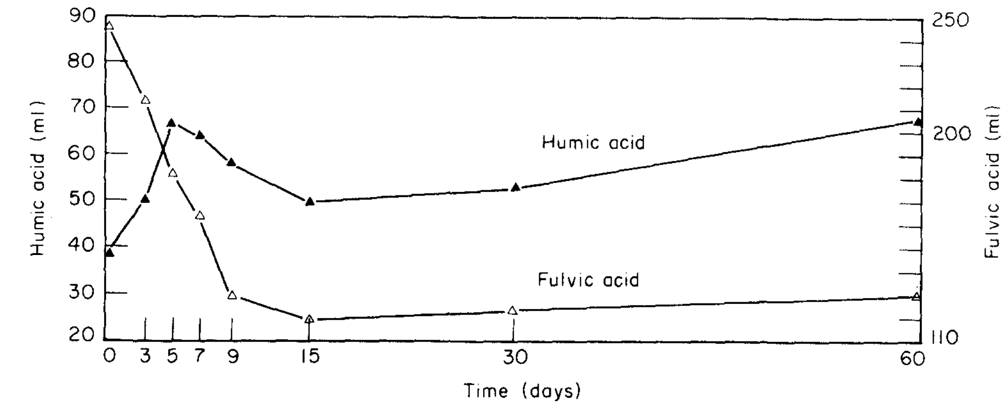

Fig. 4. Variation of humic acid and fulvic acid during composting of urban refuses (data elaborated from Sugahara & Inoko 1981).

study. The necessity for good methods by which to measure compost maturity is increasingly urgent because of the presence on the market of products sold as composts but which are not sufficiently stabilized.

Several methods, chemical, physical and biological, have been prepared for measuring compost maturity (Spohn 1978; Yoshida & Kubota 1979; Zucconi *et al.* 1981*a*, *b*; DeVleeschauwer *et al.* 1981; Sugahara & Inoko 1981; Wong *et al.* 1981; Higgins *et al.* 1982; Chanyasak & Kubota in prep.; Chanyasak *et al.* in prep.). Often chemical analyses alone are not sufficient to indicate the degree of compost maturity. Variations in particular chemical data during composting would be of greater value.

The degree of humification of the organic matter is not a good indication of compost maturity, because sometimes it does not vary very much during the process; humus undergoes a process of mineralization while new humus is being produced. Better indications are to be found by analysing humic and fulvic acids (Sugahara & Inoko 1981). The former tend to increase during composting while the latter decrease (see Fig. 4).

The presence or absence of particular physiological groups of micro-organisms within compost is by itself no indication of compost maturation. In this case too, the evolution of these microbial groups during maturation is a better indication than one final value (de Bertoldi *et al.* 1979, 1982*c*; de Bertoldi & Zucconi 1980). Biological methods for the measurement of phytotoxicity in compost is at present the most accurate and efficient method for checking on maturation of organic matter under composting (Wong *et al.* 1981; Zucconi *et al.* 1981*a*, *b*).

Biological tests on phytotoxicity using *Lepidium sativum* not only enables us to detect residual phytotoxicity in a sample analysed, but also makes it possible, through biological evolution *in vitro*, to predict the development of toxicity (Zucconi *et al.* 1981*b*). This gives us precise information on the stage of maturation which the tested compost has reached.

7. Pathogens

Solid urban waste and sewage sludge may contain high quantities of pathogenic micro-organisms which constitute a health hazard (Gaby 1975; Burge *et al.* 1978; Connery *et al.* 1979; Alderslade 1980; Lue-Hing *et al.* 1980; Dean & Lund 1981). Table 6

TABLE 6
Pathogenic micro-organisms isolated from solid urban waste and sewage sludge

Viruses	Enteroviruses
	Polioviruses
	Coxsackie
	Echoviruses
	Hepatitis A virus
	Adenoviruses
	Reoviruses
Bacteria	*Salmonella*
	Escherichia coli
	Other enterobacteriaceae
	Yersinia
	Bacillaceae
	Listeria
	Vibrio
	Mycobacterium
	Leptospira
	Campylobacter
Filamentous fungi	*Aspergillus fumigatus*
	Phialophora richardsii
	Geotrichum candidum
	Trichophyton
	Epidermophyton
Yeasts	*Candida albicans*
	Candida krusei
	Candida tropicalis
	Candida guillermondii
	Cryprococcus neoformans
	Trichosporon
Parasites	*Taenia saginata*
	Ascaris lumbricoides
	Toxocara
	Echinococcus
	Toxoplasma gondii
	Sarcocystis
	Gastrointestinal nematodes

gives a list of these micro-organisms. Sludge is generally richer in pathogens (in particular those of faecal origin) than municipal solid waste.

For compost to be freely used, the end-product must have a very low concentration in pathogens; it is also important to guarantee against regrowth of pathogens (Kawata *et al.* 1977; Millner *et al.* 1977, 1980; Burge *et al.* 1978; Connery *et al.* 1979; Cooper & Golueke 1979; Strauch & Berg 1979; Commission of European Communities 1981; Dean & Lund 1981; World Health Organization 1981; de Bertoldi *et al.* 1982*b*). If composting is correctly effected, in other words if throughout the pile a temperature of 70°C for 30 min or 65°C for several hours is reached, a sufficiently hygienized end-product is obtained (Kawata *et al.* 1977; Connery *et al.* 1979; de Bertoldi *et al.* 1982*b*).

A variety of saprophytic micro-organisms participates in the composting process. These micro-organisms may be considered the indigenous natural microflora of the compost system; solid urban waste and sewage sludge contain a second microbial population, the pathogens, which represent a numerically insignificant fraction of the total microbial population. Competition comes into play when the community is heterogeneous and the population density is high, relative to the supply of a limiting feature of the environment. The indigenous saprophytic population has a distinct competitive advantage over the other population; composting material is not the natural environment for pathogens, therefore, in this ecosystem competition will tend to result in the elimination of the less fit rival (Alexander 1971; de Bertoldi *et al.* 1982*b*). Beside this, composting greatly reduces the problem of pathogen regrowth preventing recontamination through microbial competition (de Bertoldi *et al.* 1982*b*).

8. Agricultural considerations

8.1. *Agronomical requirements of compost*

The function of organic fertilizers, such as compost, in the soil and in relation to soil-plant interaction, is quite different from that of chemical fertilizers (Kononova *et al.* 1966; McLaren & Peterson 1967; Stelly 1977; Schnitzer & Khan 1978; Harley & Scott Russell 1979; de Bertoldi *et al.* 1981; Zucconi & de Bertoldi 1982).

The main effect of organic fertilizers is not so much that of enriching the soil with N, P, K (elements which it does contain). It is rather its complex role in humus balance and so soil structure.

The main requirement for compost is that it should be suitable for agricultural use as an organic soil amendment, in other words, physical, chemical and biological stability non-phytotoxicity and balance among mineral elements are the essential characteristics for compost to be useful for the soil and for crops (Loehr 1977; Loehr *et al.* 1979; Sopper & Kerr 1979; Stefen 1979; Brinton 1979; Elfving *et al.* 1981; Zucconi & de Bertoldi 1982).

The organic fractions of composting matter must have been sufficiently humified, which is to say that they have undergone a physical and chemical transformation, in particular in the cellulose, hemicellulose and lignin proportion. It must have achieved biological stability before being used for crops. If, on the other hand, composting has only been partially effectuated or biotransformation has been anomalous, the end-product is still phytotoxic. This is due to the fact that incomplete humification of organic matter leads to intermediate products of microbial metabolism which are toxic to crops (Zucconi *et al.* 1981*a*, *b*; Zucconi & de Bertoldi 1982).

It is a well known fact that the use of green manure and ploughing-in of crop residues inhibits growth until they have undergone a process of digestion in the soil (Kononova *et al.* 1966; Rainaldi & Zucconi 1967). In pot experiments, barley emerges late in soil containing green alfalfa (lucerne) (Kononova *et al.* 1966) (Fig. 5).

Field experiments show that between 1 and 3 weeks are necessary for organic matter to be digested in the soil and that it is only at this stage that plants feel the positive effect of organic residue in the soil (de Bertoldi & Zucconi 1980; Zucconi & de Bertoldi 1982). Recent experiments demonstrate that toxicity follows a pattern: it is relatively low before composting, rises in the intermediate stage and falls to zero at the end of the process (Zucconi *et al.* 1981*a*, *b*) (Fig. 6). Different species and varieties of plants vary in their reaction to toxicity (Zucconi *et al.* 1981*b*) (Fig. 7).

Thus the need arises for rapid analyses of the physiological toxicity of immature composts. Phytotoxicity tests are the only way of evaluating physiological toxicity whether the history or composition of the starting product are known or not. This

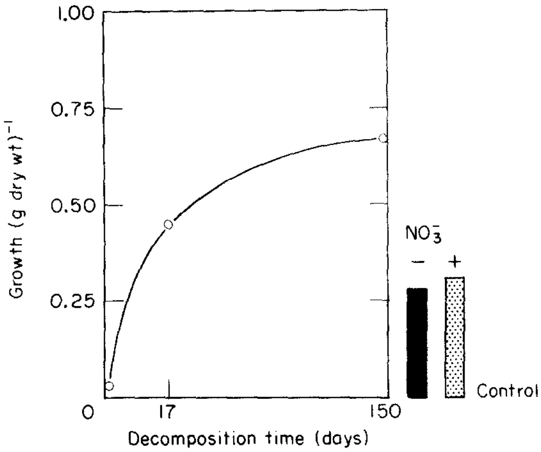

Fig. 5. Green manuring (alfalfa) causes reduced wheat growth when sown at 0–17 days interval after plowing in. Inhibition is not related to N-starvation as may be observed in control soil (histograms). Furthermore, N supplied to wheat sown at zero decomposition time does not overcome toxicity (from Zucconi *et al.* 1981*b*).

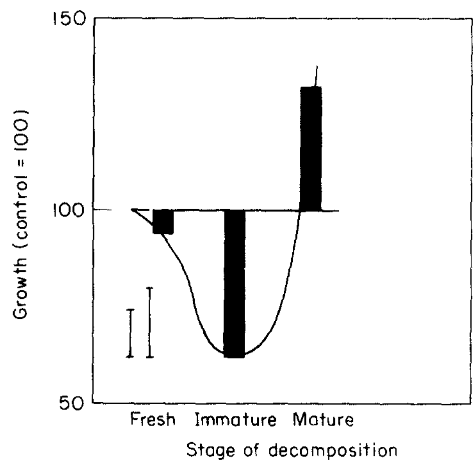

Fig. 6. Wheat germination and growth (4 days at 27°C) in contact with the organic fraction of solid waste, taken at different stages of decomposition (fresh, immature and mature compost). Bars represent least significant difference for $P = 0.05$ (left) and $P = 0.01$ (right) (from Zucconi *et al.* 1981*b*).

aim has been achieved through the use of the biotest with *Lepidium sativum* which is rapid (24 h) and can be used with low quantities of the tested sample (Forte 1980) (Fig. 8).

The absence of phytotoxicity alone is not an indication of good compost. The C/N ratio in the starting product affects the speed of decomposition and stabilization. In mature compost, the C/N ratio is important to the same extent; in fact, if it is too high (> 20), it interferes with plant nutrition in the soil because soil microflora, which are responsible for further transformation, compete with the plant roots for nitrogen.

The presence of heavy metals affects the quality and suitability of composts. These represent a high pollution risk. They also interfere with the normal physical and chemical processes in the soil and the normal physiological processes of plants when present

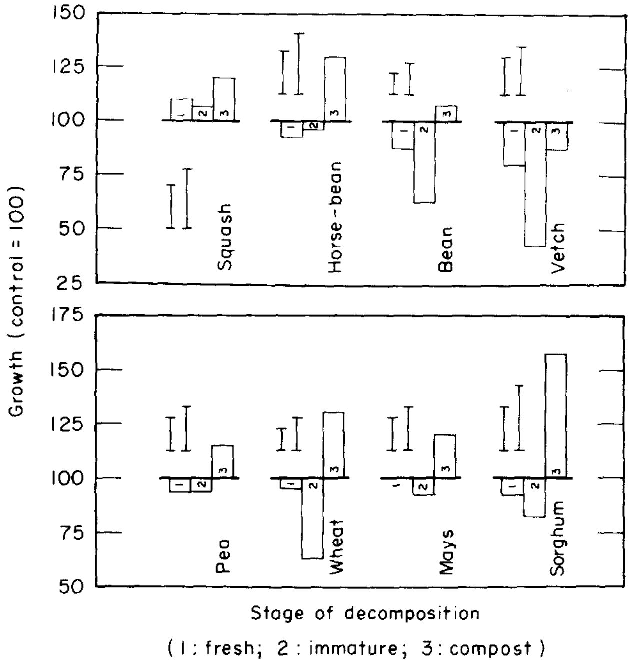

Fig. 7. Response of a number of different species to fresh, immature and mature compost underlying a perlite seed-germination bed; 5 and 1% probability least significant differences are drawn for each individual species (bars) (from Zucconi *et al.* 1981*b*).

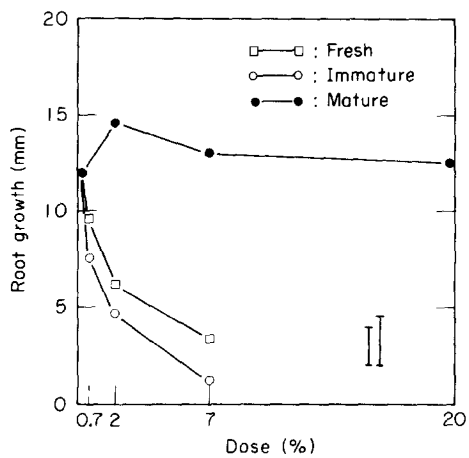

Fig. 8. Response of cress-germination test to pressure extracts from fresh, immature and mature compost. Response is strictly dose-dependent. A great differentiation between immature and mature compost is also evident (from Forte 1980).

in or above a particular concentration. If they enter the alimentary chain, they also represent a great health hazard (Baker *et al.* 1977; Chaney *et al.* 1977; Kirkham 1977; Melsted *et al.* 1977; Sidle & Kardos 1977; Webber 1979; Petruzzelli & Lubrano 1981).

The biodegradable fraction of solid urban waste is not usually a source of pollution in this respect since these potentially toxic elements are normally in such a low concentration. But sludge (particularly from industry) which is mixed with the organic fraction of solid urban waste before composting, may contain a high concentration of heavy metals (Doty *et al.* 1978; Artiola-Fortuny & Fuller 1979; Keefer *et al.* 1979; Alpert & Epstein 1982; Weir 1982). It is therefore essential that great care should be taken when composting is carried out using sludge of mixed origin (sewage and industrial).

In different countries, the law permits a maximum level of single heavy metals (Commission of European Communities 1981; Consiglio Nazionale delle Ricerche 1982).

8.2. *Growth effect of compost*

As we have already pointed out, compost has the same effect on the soil as other organic fertilizers. It improves the structure, enhancing clumping and therefore improving texture and permeability to air and water. It also improves water retention as well as binding easily leached mineral elements to the colloids of the humified fraction. It releases mineral nutrients gradually through the microbial action stimulated by the presence of organic matter. This gives soil with better nutritional qualities and improves crops. The root system is stimulated by the presence of organic matter due to improved physical and mechanical characteristics of the soil, and increased nutrition. This enables the plant to exploit a greater volume of soil resulting in an increase in the epigeous and hypogean portions (Figs 9 & 10).

Widespread international research has demonstrated an increase in yield when compost is used (Golueke 1977; Loehr 1977; Stelly 1977; Loehr *et al.* 1979).

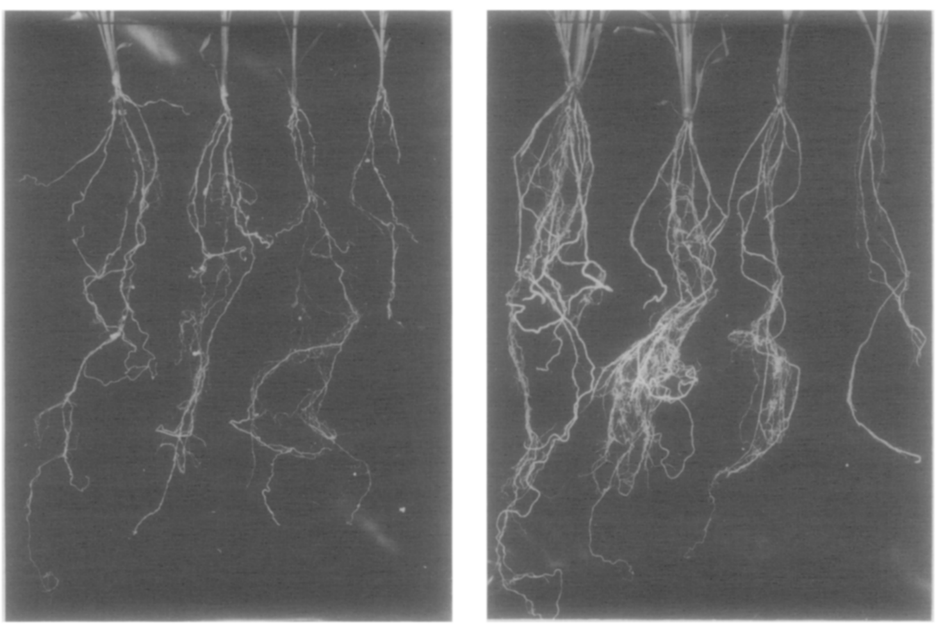

Fig. 9. Root growth of *Sorghum vulgare* in clay soil (left) and in sandy soil (right) containing increasing doses of compost from solid urban waste (read from right to left in each figure). The beneficial effect of organic matter on the root-system development is evident.

Fig. 10. Root systems of maize plants treated with mineral fertilizer (right), liquid sewage sludge (middle) and compost from solid urban waste (left). Humified organic matter, added to soil, increases the total number, length, surface area and volume of roots.

9. Conclusions

Transformation into compost of the biodegradable organic fraction of solid urban waste is one of the most validated methods of recycling. It is a process with low energy consumption and permits the disposal of the organic fraction of the solid urban waste and sludge which together represent quantitatively the greatest portion of refuse.

Composting, if correctly handled, will give a hygienically safe, agriculturally useful product. Industrial methods have been developed which produce compost in a short time that is compatible with agricultural use. In particular, a knowledge of the microbiological aspects of composting has permitted the optimization of all the factors which have a direct influence on the process.

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