Exploitation of composting management for either reclamation of organic wastes or solid-phase treatment of contaminated environmental matrices

Giovanni Vallini, Simona Di Gregorio, Antonio Pera, and A. Cristina F. Cunha Queda

Abstract: This paper is an overview of the potential use of composting technology in programmes aimed at organic waste recycling (*product-oriented perspective*) or decomposition of hazardous materials (*process-oriented perspective*). This latter approach includes composting as a tool for bioremediation of environmental matrices, such as contaminated soils and sediments. In all above-mentioned cases, biological reactions that characterize composting must be managed carefully to allow putrescible residues to become a humified agricultural fertilizer with no phytotoxic effects, or the degradation of organic pollutants (e.g., aliphatic and aromatic hydrocarbons or halogenated solvents) to proceed to the highest extent with formation of innocuous end products. Thus, the fundamental aspects of controlling the microbial environment in composting matrices are singled out as a means for better evaluating the range of adverse conditions possibly responsible for hindering the correct evolution of the process within different applications.

Key words: biopiles, bioremediation, composting, ex situ soil biotreatments, in-vessel systems, open systems, organo-nitro explosives, organic waste reclamation, polycyclic aromatic hydrocarbons, soil composting windrows.

Résumé : On présente un survol de l'utilisation potentielle de la technologie de compostage dans les programmes visant à recycler les déchets organiques (*perspective finalisée au produit*) ou la décomposition de matériaux dangereux (*perspective finalisée au processus*). Cette dernière avenue inclut le compostage comme outil de bioremédiation des matrices environnementales, telles que les sols et les sédiments contaminés. Dans tous les cas ci haut

G. Vallini[1] and S. Di Gregorio. Department of Science and Technology, Laboratories of Microbial Biotechnology and Environmental Microbiology, University of Verona, Strada Le Grazie 15, Ca' Vignal, 37134 Verona, Italy.
A. Pera. CNR, Institute of Biology and Agricultural Biotechnology (IBBA) (Sect. Pisa), Via del Borghetto, 80 56124 Pisa, Italy.
A.C.F. Cunha Queda. Instituto Superior de Agronomia, Department of Agricultural and Environmental Chemistry, Tapada da Ajuda, 1349-017 Lisbon, Portugal.

[1]Corresponding author (e-mail: giovanni.vallini@univr.it).

mentionnés, les réactions biologiques qui caractérisent le compostage doivent être aménagées avec circonspection afin de permettre aux résidus putrescibles de se transformer en fertilisant agricole humifié dépourvu d'effet toxique, ou la dégradation des polluants organiques (e.g., hydrocarbures aliphatiques et aromatiques, ou solvants halogénés) pour les transformer le plus possible avec la formation de résidus inoffensifs. Ainsi, les aspects fondamentaux du contrôle de l'environnement microbien des matrices de compostage sont examinés individuellement, comme moyen de mieux évaluer l'ensemble des conditions adverses possiblement susceptibles d'entraver l'évolution désirable du processus pour différentes applications.

Mots clés : biopiles, bioremédiation, compostage, biotraitement du sol ex situ, systèmes en bioréacteur, systèmes ouverts, explosifs organo-nitrés, recyclage des déchets organiques, hydrocarbures polycycliques aromatiques, compostage du sol en andains.

Introduction

Composting is by definition the solid-phase biological decomposition of organic residues that occurs in aerobic conditions by exploiting substrate self-heating as a consequence of microbial oxidative reactions. This process leads to the production of compost, a humus-like, dark, crumbly material that can be used as fertilizer to reintegrate organic matter in agricultural soils. Therefore, composting has long been considered an appropriate way to treat and recycle organic wastes such as crop residues, livestock manures, biodegradable fractions from municipal solid waste (MSW), sewage sludge, fish waste, pulp and paper and sawmill wastes, and by-products from a variety of food-processing industries (Vallini et al. 1984*a*, 1984*b*).

The use of composting to stabilize putrescible wastes and to transform them into a valuable resource is presently experiencing an expanding trend of application in many countries, as landfill sites become scarce and expensive and as people are more aware of the impacts that land disposal or mass burning of unsorted wastes have on the environment. In many industrialized countries, governments have already stated, or are defining, goals or legislative mandates to drastically reduce the volume of organic wastes being sent to landfills or incinerators.

Nevertheless, even lacking programmes of separate collection that allow the management of clean organic residues for high-quality compost production (product-oriented perspective), composting might be usefully applied for the stabilization of either unsorted MSW or other degradable organic matrices before landfilling (treatment-oriented perspective). The reduction in volume and the loss of putrescibility gained with a preliminary composting step make these wastes more suitable for landfill disposal, since space is saved, leachate production and biogas release minimized, and odour emission prevented.

Still in the same perspective of treatment-oriented process, composting is currently considered more and more as an important tool for the conversion of a number of chemical wastes (e.g., oil refinery sludge) (Kirchmann and Ewnetu 1998) into innocuous stabilized end products or for the detoxification of soils contaminated with noxious organic pollutants (e.g., chlorinated phenols, diesel fuel, explosives, pesticides, and polycyclic aromatic hydrocarbons) (Dooley et al. 1995; Semple and Fermor 1995; Laine and Jørgensen 1997; Vallini 1997; Bruns-Nagel et al. 2000; Fang et al. 2001; Hesnawi and McCartney 2001).

This paper examines advanced technological options for the control of the composting microbial ecosystem intended either for the treatment of putrescible organic matrices for compost production or the degradation of pollutants in both industrial wastes and soils.

Composting of organic wastes in a product-oriented perspective

Basic knowledge for process control

Although composting is often associated with sophisticated sets of machineries that determine as many different plant configurations capable of transforming organic matrices into a stabilized end

product, people should consider compost stabilization primarily as a biological process (Finstein and Morris 1975; de Bertoldi et al. 1983). This means that, if composting is to be successful, proper process design and management must be based on the fulfilment of requirements of a variety of microorganisms that represent the active agents of the stabilization reactions. Thus, optimization of composting at a biotechnological scale (i.e., improvement of decomposition rate, pathogen abatement, and odour management) requires knowledge of key factors that affect such a peculiar microbial ecosystem.

The main physical and chemical parameters that control the activity of microorganisms during composting have been extensively discussed throughout a very rich literature that has been repeatedly reviewed in the last decade (Rynk 1992; Haug 1993; USEPA 1994; Cornell University 1996; USDA 2000). On the basis of these references, the following conditions appear to be of great importance for an efficient process management: (*a*) temperature that must be considered under all aspects of external conditions, heat production within the matrix as a consequence of biological activity, heat transfer, and heat management; (*b*) moisture; (*c*) oxygen supply; (*d*) pH; (*e*) carbon to nitrogen (C:N) ratio; and (*f*) physico-mechanical characteristics of the material being composted. Moreover, if the prominent goal of composting is the production of a soil organic amendant that meets the qualitative standards for agricultural uses, then (*g*) the composition of the starting substrate biomass must be taken into account.

Temperature is probably the most important factor affecting microbial metabolism during composting. It is either a consequence or a determinant of the microbial activity. In general, composting is characterized by a first step of temperature rising, possibly to the thermophilic range ($T > 50°C$). Composting of putrescible organic wastes is typically a thermophilic process in which the most favourable range of temperatures for microbial decomposition should be maintained between 55 and 60°C and preferably should not exceed 65°C. Temperatures in excess of 55°C for several days (at least three) are usually instrumental in inactivation of pathogenic organisms, especially when septic materials such as sewage sludge are processed. Above 60°C the metabolic activity of microorganisms begins to decline. To maintain temperature within the optimal range during the thermophilic phase, substrate biomass aeration should be provided. Moving air through the matrix has the potential to dissipate heat excess. Heat removal occurs primarily via sensible heating of aeration air, while evaporation can also remove heat because of the high heat required for water vaporization.

Moisture is of crucial importance in maintaining microbial activity within a composting matrix. Optimum metabolic rates can be achieved by reaching the maximum water content that does not restrict O_2 transfer and utilization. In fact, excessively wet composting masses become anaerobic with consequent generation of unpleasant and pervasive odours. On the other hand, decomposition slows dramatically in mixtures under 40% moisture. Water content of the substrates should be 55–65% at the start of the process, with the higher values recommended for composting with turning or based on any other mechanical mixing of the substrate biomass. If the aerobic biotransformation of initial organic waste is correctly managed, moisture progressively decreases as composting proceeds towards complete biomass stabilization.

Oxygen supply allows oxidative reactions to predominate in composting matrices. Inadequate O_2 levels lead to the establishment of an anaerobic microflora, which can produce odorous compounds and phytotoxic metabolites. Substrate density and ready availability determine high O_2 utilization rates in putrescible wastes. Diffusion rates greatly depend on the matrix physical characteristics such as porosity, particle size, and moisture content. To maintain aerobic microbial metabolism, interstitial O_2 concentrations near 10% should be guaranteed.

Microbes driving compost stabilization operate best in the range of pHs between 6.5 and 8.0. Nevertheless, the natural self-correcting or buffering capacity of the process makes it possible to proceed over the much wider range of 5.5 to 9.0. Although adjustment of pH in the starting biomass is rarely required, this factor should be conditioned when matrices with high nitrogen contents are treated. Actually, pHs higher than 8.5, joined to temperatures in the thermophilic range, favour ammonification that may contribute to the unpleasant odorous emissions from composting matrices.

Of many elements required for microbial growth, carbon and nitrogen contents of a matrix are the most influential nutrients that affect substrate decomposition throughout composting. Nevertheless, these two elements have to be not only simply available, but necessarily in a balanced ratio. Generally, a C:N ratio of 25:1 to 30:1 is considered ideal for faster compost stabilization. At lower ratios, nitrogen will be supplied in excess and will be lost as ammonia, causing undesirable odours. If the carbon of a specific compostable material (e.g., lignin rich residues) is scarcely assimilable (i.e., resistant to biological degradation), a higher C:N ratio in the initial substrate biomass can still be acceptable. However, matrices with C:N ratios higher than 40:1 decompose at relatively slow rates, so longer composting times are needed.

Physical characteristics of an organic matrix being composted exert a marked influence on the course of the stabilization process. As the microbial reactions must occur in aerobic conditions, substrate biomass should always maintain adequate porosity to favour the movement of air and, hence, sufficient oxygen supply within the interstitial atmosphere. Porosity is a function of either structure (mechanical strength to collapsing) or size of the matrix particles. Thus, preliminary size reduction of compostable materials should be a good compromise between the goal of increasing the surface area-to-volume ratio of the particles, which enhances microbial decomposition rates, and the need of preventing matrix compaction because of the excessive shredding of the initial substrate. Organic wastes that are poorly structured and too wet (e.g., food residues, manures, sewage sludge) require mixing with proper bulking agents (e.g., wood chips, wood shavings, coarse sawdust) to improve porosity and mitigate moisture content.

Finally, it must be emphasised that composting should be restricted to clean organic residues if the treatment of putrescible wastes is aimed to the production of humified fertilizers. Composition of the starting matrix will greatly influence the quality of finished compost. Actually, the presence of nondegradable materials and possibly toxic contaminants in waste streams sent to a composting facility may be often irreversibly detrimental for the marketability of the end product. For instance, mechanically sorted organic fraction of MSW is still contaminated to nonnegligible extents with plastics, glass, other inerts, and chemical pollutants (e.g., heavy metals and household hazardous wastes), so it cannot lead to the production of an acceptable compost, although the stabilization process is correctly carried out. Therefore, it appears evident that production of usable compost from MSW or other composite wastes can be attained solely through activation of programmes for the collection of source-separated organic fractions.

Process control by different composting strategies for the stabilization of energy-dense and easily degradable organic wastes

Exploitation of composting as an environmental biotechnology for the management of organic wastes relies only on those systems that lead to a satisfactory control of the process. This means the achievement of high decomposition rates within relatively short stabilization times. All these systems have been developed with the attempt to ensure the basic requirements of adequate oxygen supply and temperature control in the narrow range of 55 to 65°C. In this context, composting technologies available today can be assigned to two main categories (de Bertoldi et al. 1985; Rynk 1992), depending on the arrangement of the substrate biomass during stabilization: (1) open systems, in which matrices being composted, although treated within a building, are not retained in any kind of containers and (2) in-vessel systems, in which organic wastes to be stabilized are confined in true bioreactors. Open systems include (*i*) windrow composting and (*ii*) aerated static pile composting, while in-vessel systems refer to composting performed in (*iii*) vertical reactors (e.g., silos), (*iv*) horizontal reactors (e.g., rotating drums), (*v*) box reactors, and (*vi*) aerated dynamic trenches, also known as agitated beds. The type of system to be adopted in a given circumstance depends on the land area available, the characteristics and the amount of the wastes being treated, and the estimated time required for the stabilization of the initial material. Although they are generally recognized as expensive technologies, in-vessel systems,

however, are often considered more reliable for greater process control than open systems. As it will be shown later, this is not completely true.

Windrow composting is carried out by arranging the substrate biomass in narrow elongated piles that are periodically turned. Depending on the organic waste characteristics and the turning equipment available (e.g., bucket loader, elevating-face conveyor, straddling windrow turner), windrow cross section can vary from 1.5 to 3.0 m in height and from 3.0 to 6.0 m in width, with the lower values recommended for dense materials like sewage sludge mixtures. Turning frequency is chiefly determined by windrow dimensions, matrix porosity, and moisture content. Windrows must be arranged on an impermeable concrete surface to avoid leachate dispersion into the ground and to improve equipment handling under rainy weather. Advantages of this composting system are the possibility to manage large volumes of wastes, a good stabilization of the end product, and relatively low-capital investments. Disadvantages are great land requirements, high labour costs, odour release with the turning operations, and possible failure of adequate pathogen inactivation.

Aerated static pile composting occurs in stacks shaped like windrows that are not, however, mechanically turned until the matrix stabilization has been reached. The lack of periodical mixing limits the application of this composting method to materials that can maintain a stable structure throughout the process. To improve porosity, appropriate cellulosic bulking agents such as wood chips are usually incorporated in the initial mixtures. Process control is normally performed through deliberate air delivery into the matrix by means of perforated pipes placed in a layer of coarse material at the base of the piles or embedded into the composting concrete pad underneath metal grilles. The pipes are connected to blowers that operate by timer-schedule to ensure either vacuum-induced aeration (Beltsville strategy) (Epstein et al. 1976; Willson et al. 1980) or forced-pressure ventilation. This latter strategy is often managed via feedback control of the temperature, which governs blower actuation by demand during the thermophilic phase (Rutgers strategy) (Finstein et al. 1980, 1983). Static piles should not exceed 2.5 m in height to allow homogeneous diffusion of the air through the matrix. Furthermore, it may be necessary to cover the piles with a 10 cm layer of mature compost, triturated straw, or other available bulking agent. This layer protects the composting matrix from drying, insulates it from the ambient temperature so conducing to pathogen destruction even in the outer portions of the pile, discourages flies and other insects, and acts as a sort of filter for ammonia and odours released from the pile. Of the different aerated static pile systems, only the Rutgers strategy seems to allow an optimal control of the process and, consequently, a sensible reduction of the stabilization times. This means less land requirement than in windrow composting. In general, aerated static pile systems ensure a high degree of pathogen destruction and good odour control.

Vertical and horizontal reactors specifically refer to completely closed containers in which the substrate biomass is normally retained for a few days or weeks (usually two) until only partial stabilization is reached. Closed reactors are intended to let the initial substrates overcome the early stages of composting when odour release and process control are most critical. Once out of the reactor, the composting matrix is then formed in windrows or piles to get complete maturation. These systems are usually associated with high capital and maintenance costs. Even the control of the process may be difficult as a result of heterogeneous materials such as the organic fraction of MSW being fed into the closed reactors.

In silos, substrate biomass is loaded daily at the top of the reactor while an identical volume of partially stabilized material is removed from the bottom. Aeration is typically provided by forced-pressure ventilation, with the airflow opposite to the substrate biomass flow. Nevertheless, because of the height of these reactors (usually 4.0 m), air distribution often is not homogeneous, and therefore, neither temperature nor oxygen can be maintained at optimal levels throughout the matrix profile. As with static pile composting, a stable porous structure of the substrate biomass is required in vertical reactors that normally lack internal mixing. In a few plant configurations, a second aerated silo may be considered in which the partially stabilized matrix is definitively cured.

Rotating drums are large cylindrical reactors mounted horizontally on sets of geminate bearings

that give the cylinders a slow rotatory motion by engaging special crown wheels. Rotation causes continuous mixing of the substrate biomass fed at the loading end of the reactor and allows the mixture to move through the cylinder towards the discharge end. Aeration is provided by introducing air from the discharge end. So, the air moves in the opposite direction to the substrate biomass and diffuses into the organic matrix as it tumbles. Typical dimensions of rotating drums are 3.0 m in diameter by 35 m in length, with a daily capacity of approximately 50 t and a retention time of 3 d. It is evident that such a short residence time can allow only the beginning of microbial substrate decomposition, which must be then accomplished through a second stage of stabilization, usually in windrows or aerated static piles. Therefore, rotating drums seem to function better for size reduction and as homogenizing technology than as true bioreactors. Furthermore, the difficulty of maintaining aerobic conditions in the cylinders may result in a sensible ammonia volatilization. Also substrate hygienization, emphasized as an important effect of rotating drums, might eventually prove to be a drawback if the risk of pathogen recontamination is considered. In fact, the organic matrix coming from the discharge end of the reactor is almost pasteurized and, hence, even scarcely colonized by useful microbes. Thus, once rearranged in windrows, it could be invaded again by harmful microorganisms that should not face any competition.

Recently, composting box reactors, also known as composting biocells, have been proposed on the market. They are movable containers with volumes of about 20–25 to 50–60 m^3, which can be opened and filled from the top or loaded through a door consisting of the whole front side. Usually, once fed with organic waste in the loading area, the boxes are transferred to the composting pad where each container is connected to a system for aeration through forced-pressure or vacuum-induced ventilation or a combination of both. A drainage device allows for the leachate collection. The retention times of the organic matrix inside the biocells range between 1 and 2 weeks, followed by a curing step of approximately 2 weeks in windrows (Krogmann and Krner 2000).

Nevertheless, to date, the most promising technology among in-vessel composting systems is represented by the so-called aerated dynamic trenches (agitated beds). They combine movement of the substrate biomass during composting with controlled aeration. These reactors typically consist of long, rectangular, aboveground trenches with lateral walls and open ends. The material being composted is fed at the loading end of the bed. Turning is usually effected by an overhead bridge crane running on rails along the top of the trench walls. This machine is fitted with a cylindrical cutter the same width as the trench. The position of the cutter can be regulated in height, although when operating it is set to scrape the substrate biomass up from the bottom of the trench. This material then passes onto an inclined elevating conveyor that discharges it once more in the trench behind the bridge crane as this latter moves forward on the rails. Each passage of the crane moves the organic matrix towards the discharge end of the reactor. Turning is important to break up clumps of particles, maintain porosity, and even aerate the mass. Nevertheless, oxygen supply for microbial reactions and heat dissipation are mostly guaranteed by blowing air in the composting matrix through a set of pipes recessed in the floor along the trench and covered with grilles and (or) gravel. Moreover, since the substrate biomass shows a gradient of stabilization moving from the front end to the discharge end of the reactor, the trench is often sectioned into different aeration zones along its length. Each zone is served by a blower, individually governed through feedback control of the temperature or by timer-schedule. So appropriate amounts of air can be delivered to the composting matrix according to the different stages of the process. Residence times of 5 to 6 weeks have been proven to cause complete stabilization of different mixtures of organic wastes (Vallini et al. 1990). Aerated dynamic trenches have also shown to perform efficient control of odorous emissions and pathogen destruction.

Composting application in a treatment-oriented perspective

Composting potential for the decomposition of hazardous materials

The effectiveness of composting as a means of detoxification of industrial wastes has been reported for different kinds of matrices such as tannery sludge (Vallini et al. 1989), spent mycelia from antibiotic

production, pesticide laden wastewaters (Kuo and Regan 1992), petroleum extraction and heavy oil refinery sludges (Findlay et al. 1991; Baheri et al. 1996), and coal tar (Taddeo et al. 1989; EPRI 1992). Increasingly stringent environmental regulations have made traditional disposal methods such as landfilling no longer acceptable for these wastes. In particular, as far as oil refinery sludges are concerned, even incineration and pyrolysis have often prohibitive costs.

Hazardous wastes are usually mixed with lignocellulosic bulking agents before being processed. The role of bulking materials is either to absorb liquids or to dilute concentrated dense toxic matrices. In both cases a suitable physical environment for microbial activity is created. Moreover, solid-phase substrates with large surface area are receptive to hydrophobic as well as hydrophilic compounds. Mixtures can then be placed in aerated static piles, formed in windrows, or fed to reactor vessels. If wooden cosubstrates are used, addition of nutrients such as nitrogen and phosphorus may be required. On the other hand, no nutrient supply is necessary with rich bulking materials like spent mushroom substrate (SMS), which has been utilized as both an absorption matrix and a source of active microorganisms to degrade pesticide residuals (e.g., carbamate insecticides such as carbaryl, carbofuran, and aldicarb) (Regan 1994). Typical composting temperatures are in the range of thermophily (>55°C).

Windrows or piles should always be underlain by a hard surface, and arrangements should be made for collecting and disposing of runoff and leachate from the materials. The possible release of toxic volatile organic compounds (VOCs) during the treatment should be considered, especially if turned windrow composting is adopted. Thus, confinement of the mixtures being composted should be ensured in closed buildings or shelters that can allow vapour removal by suction. Enclosure is mandatory when aromatic compounds are involved. Emissions are then treated in special scrubbers or biofilters filled with mature compost.

Composting as an ex situ soil bioremediation technology

In the last decade, composting has been evaluated as an ex situ solid phase biological technology to degrade organic compounds in contaminated soils and sediments (Hogan 1997). This treatment has given very good results with hazardous chemicals such as either aliphatic or polynuclear aromatic hydrocarbons (PAHs) (Gauger et al. 1990; Kirchmann and Ewnetu 1998), volatile solvents (Berry 1999), and explosives (Isbister et al. 1982, 1984; Williams et al. 1992).

A detailed review of the effectiveness of composting strategies in bioremediation of contaminated soils was recently presented by Semple et al. (2001). Composting bioremediation technologies have been analysed by the authors in terms of application to specific classes of contaminants such as nitro-compounds, pesticides, petroleum and aromatic hydrocarbons, and chlorophenols. The review also reported on the treatment of pollutants and polluted matrices with mature compost. Similarly, in a previous study, evidence of the microbial degradation of tar oil PAHs in mixtures of compost and contaminated soil had been provided by Meyer and Steinhart (2000).

As mentioned before, within bioremediation processes, mature compost finds a further application in the treatment of volatile compounds through biofiltration. After adsorption on the compost particles harbouring a complex microbial population, the toxic substances are degraded, until complete mineralization. Studies on the behaviours of volatile compounds on compost matrices suggested that biofilters might be successfully used for the abatement of trichloroethylene (TCE) (Sukesan and Watwood 1997) as well as benzene and toluene (Matteau and Ramsay 1997). On the basis of this preliminary evidence, compost biofiltration should represent a promising alternative in the treatment of the benzene, toluene, ethyl benzene, and xylene (BTEX) isomers fraction originating from bioventing operations on petroleum-contaminated sites.

In the evaluation of soil composting potentialities, another important aspect is that, from a climatic point of view, the process has been interestingly proved to be efficacious as bioremediation strategy even in cold environmental conditions (Berg and Eggen 1991; Berg et al. 1991).

As a rule, for soil composting activation, excavated polluted matrices (i.e., soils or dredged sediments), usually following a sieving step for the separation of stones and coarse gravel, are mixed with different kinds of bulking agents and mineral or organic amendments. They are then placed in closed temporary structures such as plastic tunnels, prepared on lined pads, or sealed with a plastic cover equipped with inlet and outlet valves for air adduction and exhausts evacuation. An obvious reason for the enclosure of the mixtures during the treatment is to prevent harmful gaseous emissions into the atmosphere and to control leachate release. Adequate amounts of water can be supplied to optimize the moisture content of the matrix. Addition of organic substrates serves both to enhance porosity of the mixtures and, possibly, to supply nutrients (C, N, P, microelements, and particular growth-eliciting compounds) for a variety of microorganisms, which may often degrade the hazardous pollutants under cometabolic conditions. Furthermore, inocula of microbes with specific degradative capabilities towards the contaminants of concern can be introduced into the matrices to be treated (bioaugmentation) to improve either efficiency or rate of abatement of the organic pollutants (Cunningham and Philp 2000).

Selection of suitable amendments is also needed to promote thermophilic microbial activity in the soil mixtures. In fact, high temperature is the most relevant feature of the composting environment, and the elevated temperatures reached during the thermophilic phase can increase the enzyme kinetics involved in biodegradation reactions. Furthermore, at composting temperatures in the range of thermophily, both solubility and mass transfer rates of the polluting compounds usually increase, thereby making them more available to the microbial metabolism. Nevertheless, evidence exists that above 60°C the number of different microbial species in the composting matrices is drastically reduced (Finstein et al. 1986). This means that mesophilic composting, in which the temperature ceiling of 37°C is established, usually presents a much richer community of microorganisms. Thus, the possible degradation of a wider number of organic pollutants should be taken into account when composting is carried out in the mesophilic range. Nevertheless, even during thermophilic composting, the dynamics of physico-chemical conditions within the composting mass determines the exposure of the polluting compounds to a variety of microorganisms. After the treatment, cleaned soils are moved again to the pristine locations.

Two basic composting systems have been implemented for bioremediation of contaminated soil: turned windrows and aerated static piles, also known as biopiles. The latter can be aerated by means of either vacuum-induced or forced-pressure ventilation. Moreover, they are particularly suitable for the bioremediation of moderate amounts of contaminated matrices. Mechanically in-vessel composting (Craig et al. 1995) and biphasic (anaerobic/aerobic) composting, either in windrows or in piles (Fischer and Walter 1999; Winterberg et al. 1998), have been also applied in successful pilot-scale experiments involving the treatment of explosives in both the U.S.A. and in Germany.

Aerated static pile composting has been shown to be successful in the abatement of aliphatic hydrocarbons in mixtures of polluted soil, sheep manure, and wood chips in the ratio of 1:1:1 (Kamnikar 1992). The process duration was protracted for 11 weeks. Forced-air biopile system was also used for the treatment of soil polluted with diesel fuel and heavy bunker oil, achieving a greater than 72% reduction of the initial contamination within a few months (Anenson 1995). Application of the biopile process even succeeded in the bioremediation of a PAHs-contaminated soil, with 75 to 83% degradation of polycyclic aromatics within 6–12 months (Eirmann and Bollinger 1995). In this case, a vacuum-induced heap system was used.

Soil composting in the presence of wood preservatives, including pentachlorophenol (PCP) and creosote, has been carried out at the University of Helsinki. Passively aerated windrows were adopted for processing soil mixed with 35% of softwood bark and 3% of vegetable ash (Valo and Salkinoja-Salonen 1986). The concentrations of chlorophenols were reduced from 212 to 30 mg kg^{-1} within four summer months. These levels were further reduced to only 15 mg kg^{-1} after an additional year of composting. The temperatures of the processed matrix fluctuated in the range of mesophily (5–32°C).

Application of composting for the treatment of soils contaminated with PAHs has been widely de-

scribed, with good results reached (Crawford et al. 1993), at least for lower molecular weight compounds (Allard and Neilson 1997). Both biopiles and windrows have been used. For instance, aerated static piles have been recently arranged at the Dubose Oil Product Co. Superfund site in Cantonment, Fla. (USEPA 1995). Composting was used in this site to treat soil contaminated with a variety of PAHs such as acenaphthylene, acenaphthene, anthracene, benzo(*a*)anthracene, benzo(*b*,*k*)fluoranthenes, benzo(*a*)pyrene, benzo(*g*)perylene, chrysene, dibenzo(*a*,*h*)anthracenes, fluorene, fluoranthene, indeno(1,2,3)pyrene, naphthalene, phenanthrene, pyrene, and 2-methylnaphthalene. Pentachlorophenol and VOCs, including benzene, xylene, trichloroethylene, and 1,2-dichloroethylene (DCE), were also present. The composting system used at Dubose consisted of soil piles arranged for forced aeration, in which native microbial population was improved through bioaugmentation with an inoculum prepared in a special tank by seeding a nutrient solution with soil aliquots. A modular pre-engineered building with reinforced PVC fabric was installed for the soil confinement. A leachate collection system was also operating. Off-gases collected by the aeration equipment were treated using granular activated carbon adsorbers prior to the discharge to atmosphere. Soil clean-up goals established for Dubose site were met. For total PAHs, before-treatment concentrations ranged from 50.8 to 576.2 mg kg^{-1}, while after-treatment concentrations ranged from 3.3 to 49.9 mg kg^{-1} (average 19 mg kg^{-1}). For PCP, before-treatment concentrations ranged from 7.67 to 160 mg kg^{-1}, while after-treatment concentrations ranged from 16.5 to 36.3 mg kg^{-1}. The primary removal mechanism identified for PAHs in this application was biodegradation; however, volatilization was identified as the main mechanism for removal of VOCs.

Finally, composting has been also proven to be successful in bioremediation of soils and sediments contaminated with organo-nitro explosives and propellants. At the Umatilla U.S. Army Depot Activity site in Hermiston, Ore. (Weston 1993), soil contaminated by the discharge into unlined lagoons of wastewater from ammunition handling, between 1950 and 1965, was treated in both aerated static pile and turned windrow configurations. Contaminants were represented mainly by 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetraazocine (HMX). After excavation, the soil was screened to remove large rocks and debris. It was then transported to a composting pad with temporary structure to provide containment. Sawdust, alfalfa, manure, and other agricultural wastes were used as amendments. The composting process occurred in the temperature range of 15 to 60°C. With the windrow method, turning was 3–7 times per week. In static piles, aeration blowers were set to cool the composting matrix whenever 60°C had been exceeded. After 40 d of treatment, composting reduced extractable explosives as follows: TNT from 1574 mg kg^{-1} to 4 mg kg^{-1} (aerated static piles and turned windrows); RDX from 944 mg kg^{-1} to 7 mg kg^{-1} (static piles) and 2 mg kg^{-1} (windrows); HMX from 159 mg kg^{-1} to 47 mg kg^{-1} (static piles) and 5 mg kg^{-1} (windrows). Therefore, windrow composting showed the potential to be the most effective method.

Another study performed at the U.S. Naval Submarine Base site in Bangor, Wash., confirms the process performances with the abatement of TNT from 822 mg kg^{-1} to 8 mg kg^{-1} after 60 d of composting in windrows (Craig and Sisk 1994) .

For a thorough overview focusing on the field-scale application of different composting technologies to the treatment of contaminated soils and sediments in North America a recent report released by EPA is strongly recommended (USEPA 2000).

Conclusions

After a few decades of debate on composting as an ecological alternative to mass burning and landfilling of garbage, solid-phase bio-oxidative stabilization of the organic fraction from such urban residue, either source-collected or mechanically sorted, represents a reliable technology for reducing the environmental impact of municipal solid waste management. Although composting cannot be looked at as an exhaustive treatment for the whole stream of urban wasted materials, it undoubtedly makes a great contribution to the solution of the problems concerned with processing of putrescibles, which represent the

most critical fraction of municipal waste. Similarly, agricultural and industrial by-products, fermentable in nature, may also be economically treated by compost stabilization and, possibly, reclaimed as organic amendants. However, a new frontier of tremendous strategic importance is now opening, which concerns microbes driving composting reactions: the exploitation of their degradative capabilities in the abatement of organic toxic contaminants in soils and sediments. Actually, addition requirements of organic amendments in the proportion of 20 to 70% by volume to the contaminated matrix impact equipment and labour costs of soil composting by the management of relatively large amounts of both the bulking materials and the resulting treated soil. However, particularly windrow composting is now considered to be, in certain cases, the most cost-effective biotreatment alternative to incineration as well as to other biological processes (Jerger and Woodhull 2000). Present evidence shows that composting appears as a very promising bioremediation technology for the cleanup of polluted sites.

Acknowledgement

References

Allard, A-S., and Neilson, A.H. 1997. Bioremediation of organic waste sites: a critical review of microbiological aspects. Int. Biodeterior. Biodegrad. **39**: 253–285.

Anenson, T.B. 1995. Biological forced air soil treatment (BIOFAST) system: a field application. *In* Proc. HAZMACON 95, 12th Hazardous Materials Management Conference and Exhibition, San José, Calif., 4–6 April 1995, ABAG, Oakland, Calif., pp. 344–353.

Baheri, H.R., Milne, B.J., and Hill, G.A. 1996. Composting of heavy oil refinery sludge. AIChE Annual Meeting, Chicago, Ill., 11–15 November 1996, Paper 51c.

Berg, J.D., and Eggen, T. 1991. Enhanced composting for cold-climate biodegradation of organic contamination in soil, EPA Forum on Innovative Hazardous Waste Technologies, Dallas, Tex., 11–13 June 1991.

Berg, J.D., Eikum, A., Eggen, T., and Selfors, H. 1991. Cold-climate bioremediation: composting for biodegradation of organic contamination at a coke work, Environmental Northern Seas Conference, Stavanger, Norway, 26–30 August 1991, Jordforsk Press, Saghellinga, Norway.

Berry, D.F. 1999. Composting of organic chemical contaminants: The bioremedial application of solid phase fermentation. *In* Bioremediation of contaminated soils. *Edited by* D.C. Adriano, Agronomy Monography 37, ASA, CSSA, SSSA, Madison, Wis., pp. 397–416.

Bruns-Nagel, D., Steinbach, K., Gemsa, D., and von Löw, E. 2000. Composting (humification) of nitroaromatic compounds. *In* Biodegradation of nitroaromatic compounds and explosives. *Edited by* J.C. Spain, J.B. Hughes, and H.-J. Knackmuss, CRC Press LLC, Boca Raton, Fla. pp. 357–393.

Cornell University. 1996. The science and engineering of composting. Dept. of Agricultural & Biological Engineering, New York State College of Agriculture and Life Sciences, Ithaca, N.Y. Available from http://www.cfe.cornell.edu/compost/science.html [updated January 2002].

Craig, H.D., and Sisk, W.E. 1994. The composting alternative to incineration of explosives contaminated soils. *In* Tech Trends, U.S. EPA 542-N94-008, Washington, D.C.

Craig, H.D., Sisk, W.E., Nelson, M.D., and Dana, W.H. 1995. Bioremediation of explosives-contaminated soils: a status review. *In* 10th Annual Conference on Hazardous Waste Research, Manhattan, Kans., pp. 168–179, (available from http://www.engg.ksu.edu/HSRC/95Proceed/craig.pdf).

Crawford, S.L., Johnson, G.E., and Goetz, F.E. 1993. The potential for bioremediation of soils containing PAHs by composting. Compost Sci. Util. **1**(3): 41–47.

Cunningham, C.J., and Philp, J.C. 2000. Comparison of bioaugmentation and biostimulation in ex situ treatment of diesel contaminated soil. Land Contam. Reclam. **8**(4): 261–269.

de Bertoldi, M., Vallini, G., and Pera, A. 1983. Biology of composting: A review. Waste Manage. Res. **1**: 157–176.

de Bertoldi, M., Vallini, G., and Pera, A. 1985. Technological aspects of composting including modelling and microbiology. *In* Composting of agricultural and other wastes. *Edited by* J.K.R. Gasser, Elsevier Applied Science Publishers, London & New York. pp. 27–40.

Dooley, M.A., Taylor, K., and Allen, B. 1995. Composting of herbicide-contaminated soil. *In* Bioremediation of recalcitrant organic. *Edited by* R.E. Hinchee, R.E. Hoeppel, and D.B. Anderson., Battelle Press, Columbus, Ohio. pp. 199–207.

Eirmann, D.R., and Bollinger, R. 1995. Vacuum heap bioremediation of a PAH-contaminated gasworks site. Soil Environ. **5** (Contaminated Soil 95, Vol. 2): 1189–1190.

EPRI (Electric Power Research Institute). 1992. Composting of coal tar contaminated soils, Phase 1: Biotreatability studies, TR-101352, Final Report. *Prepared by* Michigan Biotechnology Institute, Palo Alto, Calif.

Epstein, E., Willson, G.B., Burge, W.D., Mullen, D.C., and Enkiri, N.K. 1976. A forced aeration system for composting wastewater sludge. J. Water Pollut. Control Fed. **48**: 688–693.

Fang, M., Wan, C.K., and Wong, J.W.C. 2001. Enhancement of PAHs degradation by nonionic surfactants in composting system. *In* Ex situ biological treatment technologies. *Edited by* V.S. Magar, F.M. von Fahnestock, and A. Leeson. 6th International In Situ and On site Bioremediation Synposium, Battelle Press, Columbus, Ohio., pp. 73–80.

Findlay, M., Fyock, L., and Fogel, S. 1991. Pilot scale compost treatment of petroleum well sludge. 1991 Petroleum Symposium, University of Tulsa, Tex.

Finstein, M.S., Cirello, J., MacGregor, S.T., Miller, F.C., and Psarianos, K.M. 1980. Sludge composting and utilization/Rational approach to composting process control. Report, New Jersey Agricultural Experiment Station, New Brunswick, N.J.

Finstein, M.S., Miller, F.C., and Strom, P.F. 1986. Waste treatment composting as a controlled system. *In* Biotechnology. *Edited by* H.J. Rehm and G. Reed., Vol. 8. *Edited by* W. Schönborn., VCH, Weinheim, pp. 362–398.

Finstein, M.S., Miller, F.C, Strom, P.F., MacGregor, S.T., and Psarianos, K.M. 1983. Composting ecosystem management for waste treatment. Biotechnology, **1**: 347–353.

Finstein, M.S., and Morris, M.L. 1975. Microbiology of municipal solid waste composting. Adv. Appl. Microbiol. **19**: 113–151.

Fischer, D., and Walter, U. 1999. TNT-humifizierung Das Umweltschutz Nord-Verfahren, Werk Tanne - Erste Ergebnisse der Bodenbehandlung. Umweltschutz Nord GmbH & Co., Germany.

Gauger, W.K., Srivastava, V.J., Hayes, T.D., and Linz, D.G. 1990. Enhanced Biodegradation of Polyaromatic Hydrocarbons in Manufactured Gas Plant Wastes Proc. Gas, Oil, Coal, and Environmental Biotechnology III, New Orleans, La, 3–5 December 1990.

Haug, R.T. 1993. The practical handbook of compost engineering. Lewis Publishers, Boca Raton, Fla.

Hesnawi, R.M., and McCartney D.M. 2001. Effect of soil content on composting of diesel fuel contaminated soils. *In* Ex situ biological treatment technologies *Edited by* V.S. Magar, F.M. von Fahnestock, and A. Leeson., 6th International In Situ and On site Bioremediation Synposium, Battelle Press, Columbus, Ohio., pp. 165–172.

Hogan, J.A. 1997. Composting for soil remediation. *In* Biological treatment of hazardous wastes. *Edited by* G.A. Lewandowski and L.J. De Filippi. John Wiley & Sons, New York, N.Y., pp. 373–395.

Isbister, J.D., Anspach, G.L., Kitchens, J.F., and Doyle, R.C. 1984. Composting for decontamination of soils containing explosives. Microbiologica, **7**: 47–73.

Isbister, J.D., Doyle, R.C., and Kitchens, J.F. 1982. Engineering and development support of general decontamination technology of the U.S. Armys installation restoration program: Task II. Composting of explosives. Contract No. DAAK11-80-C-0027, ADA119276, US Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Md.

Jerger, D.E., and Woodhull, P. 2000. Applications and costs for biological treatment of explosives-contaminated soils in the U.S. *In* Biodegradation of nitroaromatic compounds and explosives *Edited by* J.C. Spain, J.B. Hughes, and H.-J. Knackmuss. CRC Press LLC, Boca Raton, Fla., pp. 395–423.

Kamnikar, B. 1992. Bioremediation of contaminated soil. Pollut. Eng. **24**(21): 50–52.

Kirchmann, H., and Ewnetu, W. 1998. Biodegradation of petroleum-based oil wastes through composting. Biodegradation, **9**: 151–156.

Krogmann, U., and Körner, I. 2000. Technology and strategies of composting. *In* Biotechnology. 2nd Completely Revised Edition. *Edited by* H.J. Rehm and G. Reed. Vol. 11c. *Edited by* J. Klein and J. Winter, VCH, Weinheim., pp. 143–144.

Kuo, W.S., and Regan, R.W. 1992. Degradation of carbaryl and 1-naphthol by spent mushroom compost microorganisms. Water Sci. Technol. **26**: 2081–2084.

Laine, M.M., and Jørgensen, S. 1997. Effective and safe composting of chlorophenol-contaminated soil in pilot scale. Environ. Sci. Technol. **31**(2): 371–378.

Matteau, Y. And Ramsay, B. 1997. Active compost biofiltration of toluene. Biodegradation, **8**: 135–141.

Meyer, S., and Steinhart, H. 2000. Effects of heterocyclic PAHs (N, S, O) on the biodegradation of typical tar oil PAHs in a soil/compost mixture. Chemosphere, **40**(4): 359–367.

Regan, R.W., Sr. 1994. Use of SMS as a compost matrix to degrade pesticide residuals. Compost Sci. Util. **2**(3): 56–62.

Rynk, R. (*Editor*). 1992. On-farm composting handbook. Northeast Regional Agricultural Engineering Service, Cooperative Extension, Ithaca, N.Y., pp. 24–42.

Semple, K.T., and Fermor, T.R. 1995. Composting systems for the bioremediation of chlorophenol-contaminated land. *In* Bioremediation of recalcitrant organics. *Edited by* R.E. Hinchee, R.E. Hoeppel, and D.B. Anderson, Battelle Press, Columbus, Ohio., pp. 93–100.

Semple, K.T., Reid, B.J., and Fermor, T.R. 2001. Impact of composting strategies on the treatment of soils contaminated with organic pollutants. Environ. Pollut. **112**: 269–283.

Sukesan, S., and Watwood, M.E. 1997. Continuous vapor-phase trichloroethylene biofiltration using hydrocarbon-enriched compost as filtration matrix. Appl. Microbiol. Biotechnol. **48**: 671–676.

Taddeo, A., Findley, M., Dooley, M., and Fogel, S. 1989. Field demonstration of forced aeration composting treatment for coal tar. 1989 HMCRI Superfund Conference.

USDA. 2000. National Engineering Handbook, Chapter 2, Composting. *Edited by* R.E. Graves. Natural Resources Conservation Service National Production Services, Fort Worth, Tex.

USEPA. 1994. Composting yard trimmings and municipal solid waste, Chapter 2, Basic composting principles. Office of Solid Waste and Emergency Response, EPA530-R-94003, Washington, D.C.

USEPA. 1995. Composting Application at the Dubose Oil Products Co. Superfund Site, Cantonment, Florida. Cost and Performance Report, U.S. EPA/Office of Solid Waste and Emergency Response, Technology Innovation Office, Washington, D.C.

USEPA. 2000. Innovative Remediation Technologies: Field Scale Demonstration Projects in North America, 2nd Edition/Year 2000 Report. Office of Solid Waste and Emergency Response, EPA542-B-00-004, Washington, D.C.

Vallini, G. 1997. Microbiology of solid-phase treatments in soil bioremediation: the composting option. ICS-UNIDO Report, Training Course in Soil Environmental Assessment and Biodegradation Technologies, Budapest, 2–14 June 1997.

Vallini, G., Bianchin, M.L., Pera, A., and de Bertoldi, M. 1984*a*. Composting food factory, fruit and vegetable waste, tannery sludge and cork waste. Seminar on Composting of Agricultural and Other Wastes, Oxford, 19–22 March 1984, Commission of the European Communities, DG XII, Programme on Secondary Raw Materials, Brussels.

Vallini, G. Bianchin, M.L., Pera, A., and de Bertoldi, M. 1984*b*. Composting agro-industrial by-products. Biocycle, **25**(4): 43–46.

Vallini, G., Pera, A., Sorace, G., Cecchi, C., and Manetti, P. 1990. Source-collected vegetable waste: Green composting. Biocycle, **31**(6): 33–35.

Vallini, G., Pera, A., Cecchi, F., Briglia, M., and Perghem, F. 1989. Compost detoxification of vegetable-tannery sludge. Waste Manage. Res. **7**: 277–290.

Valo, R., and Salkinoja-Salonen, M. 1986. Bioreclamation of chlorophenol-containing soil by composting. Appl. Environ. Microbiol. **25**: 68–75.

Weston, R.F. . 1993. Windrow Composting Demonstration for Explosives-Contaminated Soils at the Umatilla Depot Activity, Hermiston, Oregon. Final Report, Prepared for USAEC, Contract No. DACA3191-D-0079, Report No. CETHA-TS-CR-93043.

Williams, R.T., Zieganfuss, P.S., and Sisk, W.E. 1992. Composting of explosives and propelant contaminated soils under thermophilic and mesophilic conditions. J. Ind. Microbiol. **9**: 137–144.

Willson, G.B., Parr, J.F., Epstein, E., Marsh, P.B., Chaney, R.L., Colacicco, D., Burge, W.D. Sikora, L.J., Tester, C.F., and Hornick, S. 1980. Manual for composting sewage sludge by the Beltsville aerated-pile method. EPA/600/8-80-022, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Winterberg, W., von Löw, E., and Held, T. 1998. Dynamisches Mietenverfahren zur Sanierung von Rüstungsaltlasten. Terratech, **3**: 39–41.