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Preface

This book came about as the editors discussed the substantial advances that the science of composting has experienced during the last few years. These discussions led to the identification of the need for a book that would present a thorough, objective description of the status of composting. Consequently, the editors took upon the task of soliciting contributions from some of the leading scientists involved in various aspects of composting throughout the world.

As it will become evident by reading this contribution, the editors are confident that the key objective has been met. The compilation of the various chapters has been enjoyable and the process has allowed the editors to have the pleasure of working closely with several colleagues. We hope that this book will be of use to those involved in teaching, designing, operating, and monitoring composting facilities worldwide.

Chapter 1

Introduction

L.F. Diaz

1.1. Principles

During the past few years, many government entities throughout the world have developed and imposed regulations requiring that communities reach levels of recycling that typically fluctuate between 15 and 50% of the quantities of wastes generated by the community. To achieve these levels of recycling or diversion of waste from the landfill in an efficient and cost-effective manner, it is necessary to plan and implement an overall waste management program such that its various elements are compatible with one another. Compatibility of the elements of the program has led to the widespread use of the term "integrated" waste management. In solid waste management nomenclature, the term "integrated" would be reserved for systems, schemes, operations, or elements in which the constituent units can be designed or arranged such that one meshes with another to achieve a common overall objective. Moreover, the forming or blending must be such that it establishes a community-wide or region-wide hierarchy for integrated waste management. In many instances, integration has been misinterpreted and has focused on primarily the treatment of the solid waste, i.e., source reduction, recycling, and composting. However, a fully integrated waste management program encompasses much more than treatment. A successful integrated program must consider other technical aspects such as storage, collection, transport, processing, and final disposition. All of these elements must be developed such that they are compatible with one another. In addition, other relevant non-technical components such as behavioral patterns, economic conditions, financial aspects, public education, public relations, and training must strategically support the technical aspects (Diaz et al., 1982a,b).

Integration implies a design, such that the activity or operation as a whole functions harmoniously, and efficiently — each unit contributing and complementing its neighboring unit. A major portion of this chapter is devoted to explaining the relationship between true integration and beneficial outcome. Emphasis is placed on composting as a key component of integrated solid waste management.

1.1.1. Definitions and Meanings

A discussion on integrated waste management — or any other integrated system or activity — should start with some description about the true meaning of integration. Unfortunately, "integrated" has become a popular term and, consequently, one is almost sure to encounter the term in the labels and titles of proposed waste management undertakings and even in those of some not-so-new undertakings. Before continuing the discussion, it should be emphasized that the term "integrated" implies more than a collection of unrelated or independently functioning units under a single roof — or management. Of course, such an interpretation is an exaggeration, but it does serve to illustrate the misuse of the term and set the stage for discussing its true meaning and implications.

Of the four versions of the definition of the verb "to integrate," the one that is probably most appropriate to the purposes of this chapter is: "to form or blend into a whole." Moreover, the forming or blending must be such that overlapping is at a minimum and each unit functions at full capacity without interfering with other member units. On the contrary, each unit must function in such a manner that the functioning of the other constituent units is facilitated.

From the preceding definitions and discussion, it is apparent that "integrated" is not synonymous with "complex;" it does not imply any particular set of dimensions. Thus, an integrated solid waste management operation or system possibly could involve only a few unit operations. An example could be one involving only storage, collection, and disposal under a single management (i.e., individual or corporation). However, in modern usage, the trend is to expand the application of the term to include the non-technical (i.e., managerial, economic, social, cultural, and other factors), as well as the technical aspects of waste management.

1.1.2. Distinction between Integration and Strategy

The discussion of definitions and meanings is ended with a few words on the distinction between integration and strategy. With respect to the distinction, integration refers to the doing, whereas strategy implies how to go about making the integration. Thus, strategy may determine the type of a particular approach or it may be a pattern for integration.

1.1.3. Relationship between Integration and Beneficial Effects

Our discussion on the principles of integration is designed to show the inherent relationship between integration and the benefits associated with it. Integration accomplishes its beneficial effects by reducing complexity to simplicity through unification of order from disorder and uniformity from diversity. Simplicity and order do not leave room for overlapping or unnecessary duplication of functions. By doing so, it promotes efficiency. Increasing the level of efficiency, in turn, conduces a lowering of requirements. Regarding efficiency, the following especially comes to mind: equipment capacity, energy consumption, maintenance requirements, and land usage. Additional meanings and other implications of these beneficial effects become more comprehensible, and therefore apparent, as our discussion progresses.

With respect to benefits, it should be emphasized that the present situation in solid waste management is such that all of the benefits associated with integration are essential to the success of practically all solid waste management undertakings, especially those that involve resource recovery. In conclusion, the scarcity of available land and the existence of severe siting problems for final disposal facilities have become so acute as to make resource recovery imperative in many situations. Therefore, it follows that a high level of integration must be a feature of current and most future solid waste management undertakings (Golueke et al., 1980; Diaz et al., 1982b, 1987; Savage, 1990).

1.2. The Role of Composting

As it will be described in other chapters, composting has been used for many years throughout the world in the stabilization of organic residues. Initially, in the management of municipal solid waste (MSW), the emphasis was on composting the organic fraction of MSW; sewage sludge (biosolids) was regarded principally as a source of nitrogen and phosphorous, and to a lesser extent of potassium for enriching the organic matter and thus promoting the compost process (Rodale, 1943; Truman, 1949; Golueke, 1950, 1953, 1972, 1977).

The first medium- and large-scale processes were designed to treat the entire municipal solid waste stream. It is possible that the designs of the facilities were appropriate at that time since the major constituents of the MSW were of biological origin. Unfortunately, the designs of the treatment facilities were not modified as the characteristics of the waste changed in primarily industrialized countries. The characteristics of the waste along with other factors led to the closure of several facilities in North America and in Western Europe.

The second half of the 1970s witnessed a drastic shift in the emphasis of composting. Facilities were designed to treat a number of substrates ranging from manures to the organic fraction of MSW to biosolids. In the USA, the shift was largely a response to a desperate need for a means of treating biosolids other than by way of incineration or landfill. Composting seemed to meet the need, especially since biosolids treatment had been considerably advanced, particularly with respect to dewatering. In the new setting, biosolids were dewatered to a concentration of total solids at which composting became feasible provided that a bulking agent was used. Although not particularly troublesome at first, this stipulation eventually became a financial handicap. With the worsening of the financial viability came a renewed interest in the possibility of composting refuse. It is not surprising that the possibility of bypassing the requirement for bulking by using the organic fraction of refuse as a bulking agent gained attention (Golueke, 1977; Cal Recovery Systems, 1983; Goldstein, 1987).

Legislative mandates, recycling goals, protection of the water and soil resources, and other objectives set forth by national, state, and local governments provided the impetus for waste managers to look for alternatives to reduce the amounts of waste disposed on the land. Given the quantities and characteristics of the wastes generated by urban areas (i.e., relatively large quantities of organic matter), biological treatment, in particular composting, provides a sound, cost-effective, and efficient process.

As it will be explained in future chapters, composting offers a large number of advantages and few disadvantages for treating organic residues. Composting can be carried out at different levels of technology and at different scales (from backyard to central facilities). Furthermore, the compost product can be put to use in a great number of applications in various geographical areas throughout the world.

1.3. Conclusions

Integration of various processes is a necessity in order to meet high levels of waste diversion and reduce our reliance on land disposal. A relatively large quantity of solid wastes consists of organic materials. Collection and treatment of the organic fraction of MSW can help meet regulatory and other requirements associated with reduction of the quantities of waste reaching the landfill. Composting is a relatively simple and cost-effective method of treating organic wastes. In addition, composting offers a number of benefits among which are: increase of the lifespan of the disposal site, reduction of the quantity and quality of leachate produced in a landfill, and reduction in the quantity of gas produced in the landfill.

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Chapter 2

History of Composting

L.F. Diaz and M. de Bertoldi

2.1. Neolithic Period and Early Civilizations

The history of urban waste generation and its management begins with human civilization and urbanization.

During the Neolithic period, human beings for the first time began to live in urban settlements, changing their habits from essentially hunters and gatherers to farmers and breeders. Since the establishment of these settlements, waste pits became commonly used. The first waste pits made out of stone and built outside the houses were found in Sumerian cities about 6000 years ago. In these pits, organic urban waste was stored for eventual application on agricultural fields (Uhlig, 1976; Martin and Gershuny, 1992).

The early civilizations in South America, India, China, and Japan practiced intensive agriculture and it is known that they utilized agricultural, animal, and human residues as fertilizers (Howard, 1943; Food and Agriculture Organization, 1978). Many of these residues either were placed in pits or placed in heaps and allowed to rot for long periods of time for the production of a soil amendment.

An analogous function has been suggested for the large pits found at Knossos, Crete, Minoan–Mycenaean civilization, 1800–1200 BC, by the city's gate (Wilson, 1977; de Bertoldi and Zucconi, 1986).

Imperial Rome, a city that at the height of its power had about one million people, developed advanced systems for urban waste management, organized and supported by the state administration. In order to preserve hygienic conditions in the city, urban waste was collected periodically by a permanent staff, discharged outside the town, and eventually applied to agricultural soils.

Similarly, in pre-Renaissance Florence, farm wagons transported food to the town in the morning and departed the city in the evening with loads of garbage to be applied on the farms (Altomonte, 1982).

However, one of the most accurate and technical descriptions of "composting" has been conducted by the Knights Templar of the thirteenth century. The Templars were a military order during the time of the Crusades. When the Moslems occupied the Holy places in Palestine, the Templars settled in Spain and in the south of France, where they devoted much of their time to agriculture. They rented farms, some of which had been devastated by the Moslems during their retreat from Spain and had not been cultivated for many years. The contracts for renting the land, for the donations, and the various clauses on how to recover the depleted soils were written in Codex. Some of these documents still exist in archives such as the National Library of Madrid, the Historic National Archives of Madrid (series B and R of Codex); manuscripts in the Cistercian Abbeys of Fitero, Poblet, Sates Crues, Huerta; and Archives of Caceres Deputation, manuscripts of the biggest "Commanderie" farm of Templars in Alcanedre, Extremadura, Spain (de Bertoldi, 1999). These manuscripts, transcribed in the thirteenth century, report the techniques used by the Templars to recover fertility in arid and depleted soils. The description of composting systems starts with the preparation of different starting materials in order to obtain many types of composts to be used on different crops — particle size, length, and diameter of chipped branches. The ratios between wood and animal manure and moisture are carefully determined. After the preparation of the starting mixture for composting, exact indications of windrow dimensions are reported, both with triangular and trapezoidal cross sections. The windrows were covered with branches or soil during the process in order to reduce moisture loss through evaporation. Treatment times for single materials are reported, and the documents suggest the use for the compost (quantity and application times) for each vegetable or fruit tree.

It is interesting to note the accuracy of the description in the documents, especially if we consider that at that time microbiology and soil chemistry were unknown. Nevertheless, through the description given by the Templars on the production of composts and their use for soil improvement, it can be assumed that the Templars well understood various aspects of geology, soil biology, the art of composting, and the basic elements of agronomy and soil fertility (Dailliez, 1981).

To find more detailed and scientific descriptions of composting than those given by the Templars, we now discuss advances made during the twentieth century.

2.2. Twentieth Century

One of the first documented efforts on the application of composting in the management of organic residues began in India in 1933. At that time, Sir Albert Howard made the first major advance in the history of modern composting (Howard and Wad, 1931; Howard, 1933, 1935, 1938). Sir Howard, in collaboration with Jackson, Wad, and other workers (Hegdekatti, 1931; Jackson and Wad, 1934; Watson, 1936; Duthie, 1937; Aranjo, 1948), developed the composting procedures into a method known as the "Indore process" (Brunt, 1949). The method was known by that name because of the locality in which it was first put into practice. Initially, the Indore process used only animal manure, but later it involved stacking alternate layers of readily biodegradable materials on open ground. Some of these materials included human feces (nightsoil), garbage, and animal manure. The process also included straw, leaves, municipal refuse, and stable wastes. The materials to be composted were piled to a height of about 1.5 m or were placed in specially constructed pits 0.6–0.9 m deep. Initially, the composting process lasted 6 months or longer, during which the material was aerated only two times. The leachate that would drain from the composting material was recirculated and used to control the moisture in the piles. It is possible that the composting piles were aerobic for only a short period of time at the beginning of the process and after each turn, and were anaerobic during most of the remainder of the composting process. The Indore process was modified and widely used in India by Ayyar (1933), Howard (1938), Acharya and Subrahmanyan (1939), Acharya (1950), and others (India, Ministry of Agriculture, 1949). Later, the Indian Council of Agricultural Research at Bangalore, during the time that it was developing the composting process in that country, improved the Indore method and named it the "Bangalore process." Scharff in Malaysia (1940), Wilson (1948), and Blair (1951) in South Africa, and others in various parts of the world (Aranjo, 1948; Anonymous, 1948; New Zealand, Inter-Departmental Committee on Utilization of Organic Wastes, 1951; Weststrate, 1951; Wylie 1952, 1953) conducted several studies of the Indore method, made some modifications to the method, and evaluated the use of the finished compost as a fertilizer. An important modification to the Indore method was the use of more frequent turning in order to maintain aerobic conditions, thus achieving more rapid degradation and shortening the composting period.

In 1935, Scott and others carried out studies of composting in relation to agricultural sanitation in Northern China. Practically all of their studies used nightsoil. These efforts were discontinued in 1941 due to World War II. Fortunately, the results of their studies were published (Scott, 1952). The results of the work conducted by Scott and his colleagues provided important information on problems dealing with composting human wastes and other residues in rural areas.

Waksman and his colleagues performed basic research on aerobic decomposition of vegetable residues and stable manure from 1926 to 1941. They made and reported important discoveries regarding the influence of temperature on the rate of decomposition (Waksman, 1938; Waksman et al., 1939a,b), the role of individual groups of microorganisms (Waksman and Cordon, 1939), and the effect of mixed cultures as compared with pure cultures (Waksman and Cordon, 1939; Waksman et al., 1939a) on the breakdown of organic matter (Waksman, 1952).

One of the first publications dealing with composting in the United States was Bulletin No. 61 by the North Carolina Agricultural Experiment Station published in 1888 entitled: *XI. Composts – Formulas, Analyses and Value*. A considerable amount of research also was carried out at the Connecticut Agricultural Experiment Station, which led to the publication in 1949 of a special soils bulletin entitled "Principles of Composting" (Maynard, 1994).

From 1950 to 1955, Golueke and his associates at the University of California at Berkeley conducted basic and applied research on some of the most important aspects of composting mixed municipal refuse, food residues, and other biodegradable matter, both with and without the addition of biosolids (University of California, 1953; Golueke, 1954; Golueke and Gotass, 1954; Golueke et al., 1954; McGauhey and Gotaas, 1955). Their investigations made significant contributions to the knowledge of modern composting. The results of the work conducted by these researchers demonstrated the effects of some of the different variables encountered in aerobic composting, such as: temperature, moisture content, aeration by turning and by other means, the carbon-to-nitrogen ratio of the organic materials, the use of special biological inocula, and the impact of size reducing the material. For example, they demonstrated that turning the material at fairly frequent intervals during the first 10–15 days of composting resulted in approximately the same degree of stabilization as making the same number of turns over a longer time period (University of California, 1953). Furthermore, they also demonstrated that a higher level of aeration during the initial stages of degradation increased microbiological activity, shortened the period of active decomposition, and consequently reduced the time and land area needed for composting. Their studies also provided data on the types of organisms present in composting, techniques for evaluating the condition of the compost during and after the operation, the insulating and heat retention characteristics of compost materials, and various considerations for process design (Golueke, 1954).

In the 1950s, work was also carried out on determining the utility of adding enzymes to promote digestion (Heukelekian and Berger, 1953).

At the same time that the early composting methods were being refined in India, China, Malaysia, and in other countries, other investigators, particularly in Europe, were devoting considerable effort to mechanizing the composting process. Mechanization was developed for the use of composting as a method for the treatment and sanitary disposal of MSW. These efforts resulted in several mechanical innovations. Some of the main objectives of these processes were: to improve the aesthetics of the composting process by enclosing the material in some type of structure, to reduce the amount of time required to stabilize the composting material, and to make it more economical. The mechanized and enclosed processes were designed primarily for application in urban areas.

One of the most widely used of the early-patented processes was developed by Beccari (1920) of Florence, Italy, and was known by his name (Boniface, 1929; Engineer (Lond.), 1930; Hyde, 1932; University of California, 1950a; Perold, 1951). In the process, the material to be composted was placed in an enclosed cell in order to control the escape of foul odors associated with the breakdown of organic matter. The process used an initial anaerobic fermentation phase followed by a final aerobic stage. As originally designed, the Beccari unit consisted of a simple cell-type structure. The structure had a loading hatch on the top and an unloading door in the front. Air vents were included in the cell that, when opened for the final stage, were supposed to allow composting to proceed under partially aerobic conditions. The Beccari process had installations in Italy and in France (University of California, 1950a).

In the time period from 1920 to 1930, five municipalities located in Florida and in New York, USA attempted to employ the Beccari process (University of California, 1950a).

In pilot-scale demonstrations of these cells by licensees of the firm, Brevetti-Beccari-Voltancoli, S.A. of Florence, it was demonstrated that a wide variety of organic residues could be disposed of without nuisance. However, when a full-scale plant was built in Scarsdale, New York (University of California, 1950a,b), it was found that anaerobic conditions eventually developed in the composting mass, resulting in extremely foul odors when the doors were opened. The plant was temporarily abandoned and later modified. Unfortunately, the modifications made on the full-scale installation were not able to control the problems related with noxious drainage. Eventually, the New York Health Department intervened and closed down the facility (University of California, 1950a).

Reproductions of photographs taken of the Beccari process in the late 1920s and early 1930s are shown in Figs 2.1 and 2.2.

A modification of the Beccari process, providing for recirculation of the leachate or of gases and possibly providing more aeration, was known as the Verdier process.

In 1931, Bordas made additional modifications to the Beccari process (University of California, 1950a). Bordas' plans were to eliminate the anaerobic stage of the Beccari process by introducing air into a fermentation silo by means of pipes placed along the middle and along the walls of the silo. A grate was also incorporated in the design to divide the silo into an upper and a lower section. Compost was produced on a batch basis with maximum use of the silo. This was accomplished by discharging the composting material through the grate into the lower chamber, when the organic matter had lost much of its volume by decomposition.

In 1939, Earp-Thomas of Hampton, New Jersey, USA patented a digester for producing compost under aerobic conditions. The digester was of the silo-type equipped with multiple grates. The unit made use of rotary ploughs and forced air for aeration. A basic feature

Fig. 2.1. View of Beccari cells at Florence, Italy (Source: University of California 1950a).

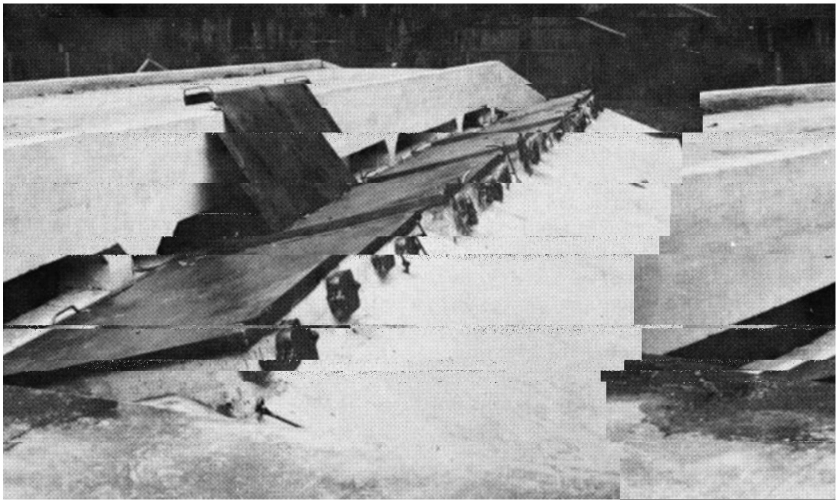

Fig. 2.2. View of process installation at South Jacksonville, Florida, USA (Source: University of California 1950a).

of the process was the use of "special" bacterial cultures, which were also supplied by Earp-Thomas. A schematic diagram of the Earp-Thomas digester is presented in Fig. 2.3.

The Ralph W. Kiker Company of Lansing, Michigan, USA designed a variation of the enclosed-cell digester. The digester consisted of a silo with double walls and with multiple floors. The organic material was introduced into the inner silo, was aerated internally and externally, and at the same time was continuously sprayed with leachate from the composting process pumped from a collection sump. It is reported that a special inoculum was to have been involved in this process (University of California, 1950a).

In 1949, the Frazer process was patented in the USA (Eweson, 1953). In the process, shredded organic matter was introduced into an enclosed, fully mechanized, aerobic digester. The organic matter was continuously mixed as it moved downwards from one level to another. The composted material was screened as it left the digester and the "residue" from the screening process was returned to the composting process.

The Hardy digester consisted of a large cylinder containing augers. The augers were hollow and were mounted perpendicular to the floor, for both aerating and for mixing the material. The bottom of the cylinder was porous in order to allow air to enter and leachate to flow out. Aerobic decomposition of the organic matter took place in the digester. The unit was operated on a continuous basis. The finished compost was discharged as raw material was added to the top of the cylinder. There were other digesters that were patented. Each one of the units had different approaches for aerating and handling the material (University of California, 1950a).

A photograph of the Hardy digester is shown in Fig. 2.4. A view of augers used for mixing and aerating in an empty digester shown in Fig. 2.5 and a view of the augers mixing a filled digester in Fig. 2.6.

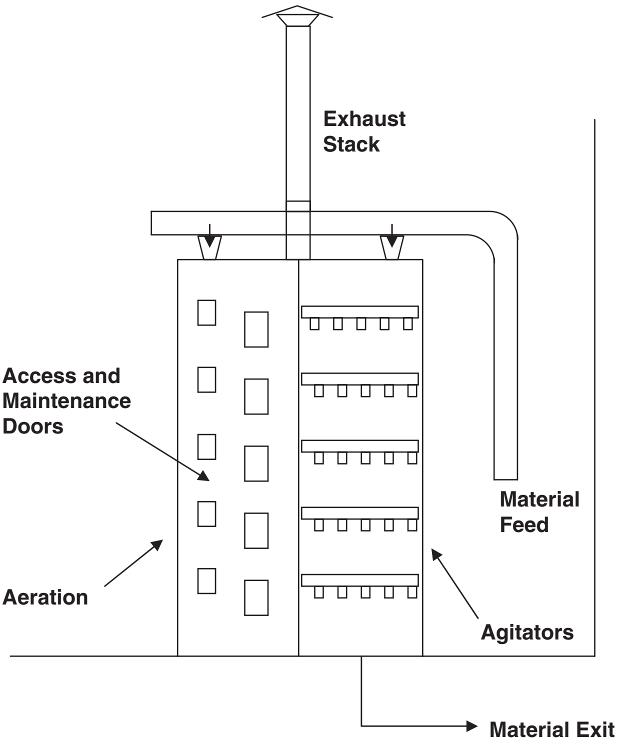

Fig. 2.3. Schematic diagram of the Earp-Thomas digester.

Several experimental studies were conducted on composting in a silo-type digester using mechanical mixing (Snell, 1954). The result of this work demonstrated that a substantial amount of attention had been paid to the development of more efficient mechanical stirring and to the solution of mechanical problems associated with digester operations. It seems that, at that time, silo digesters had been used primarily in relatively small installations for segregated waste having a high concentration of organic matter. The processing units were highly mechanized in order to provide continuous aeration, and were designed to try to reach thermophilic temperatures in order to achieve rapid degradation.

A process that was heavily marketed and used in a number of countries throughout the world was the Dano process. This process was developed in Denmark and was generally referred to as a composting process; however, it essentially was an operation for segregating and size reducing the refuse. The output from the operation could be composted by any of the procedures available at that time. In the process, the refuse was fed into a slowly rotating cylinder, with the axis sloping slightly downwards from the horizontal, where the material was aerated to remove odors, mixed, and was partly broken up into smaller particles. The ferrous metals and other recyclable materials were removed by a magnetic separator and hand sorting as the material passed to a grinding and homogenizing machine,

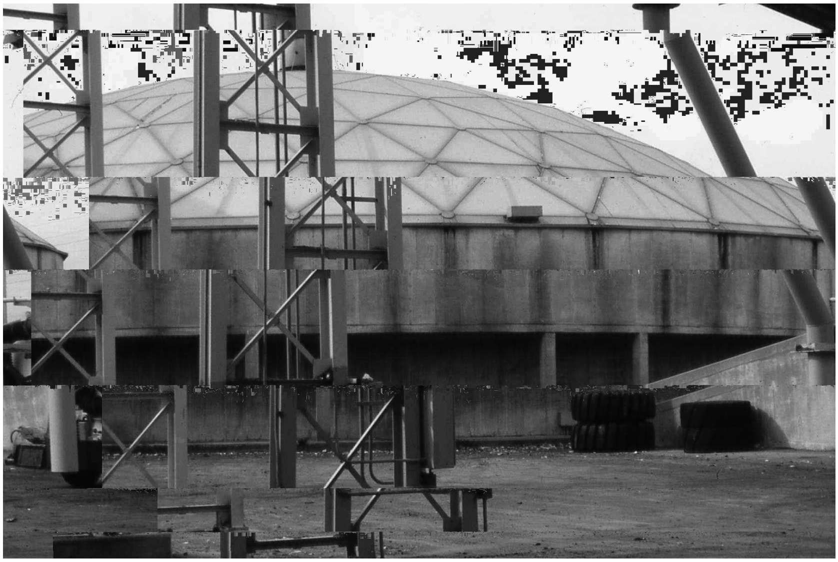

Fig. 2.4. Partial view of the Hardy digester (Delaware, USA).

Fig. 2.5. View of augers inside Hardy reactor (Delaware, USA).

Fig. 2.6. Augers mixing a full digester (Delaware, USA).

known as the Egsetor. Size reduction to a desired size of particle was accomplished by friction between the particles of refuse and between the refuse and the roughened walls of the rotating Egsetor. It took 4–6 h for the material to go through the grinding machine. The actual composting took place in piles on the ground to heights of 1.5–1.8 m.

The Dano Corporation later developed a mechanical silo-type digester known as the Bio-stabilizer (Dano Corporation, 1955). Initially, the unit operated on a pilot-plant scale, composting approximately 20 tons of refuse per day. The Bio-stabilizer unit basically consisted of a long cylinder, similar to a cement kiln, which rotated slowly (about one revolution every 5 min) and was inclined slightly downwards from the horizontal. Refuse, with or without the addition of sewage sludge, was introduced into the digester. The digester had a capacity for about 100 tons of wastes and generally was maintained as substantially full. As the unit rotated, the wastes traveled slowly forward. Liquid could be added to the digester to control the moisture content of the composting mixture. Aeration was achieved by means of two rows of air jets located along the length of the cylinder. Size reduction of the wastes was achieved by abrasion of the rotating particles and by biological action. The refuse was kept in the digester for about 3–4 days, depending upon the type of material. The temperature of the material was maintained within the thermophilic range during most of this time. At the discharge end of the Bio-stabilizer, the compost was passed through a 1-cm mesh screen. The output from the unit was stabilized further, if required, by placing it in windrows. A small Bio-stabilizer plant was built in Ruschlikonk, Zurich, Switzerland; a larger plant was built in Edinburgh, Scotland; and an experimental installation was built near Los Angeles, California, USA. Later, several facilities were built in various countries throughout the world.

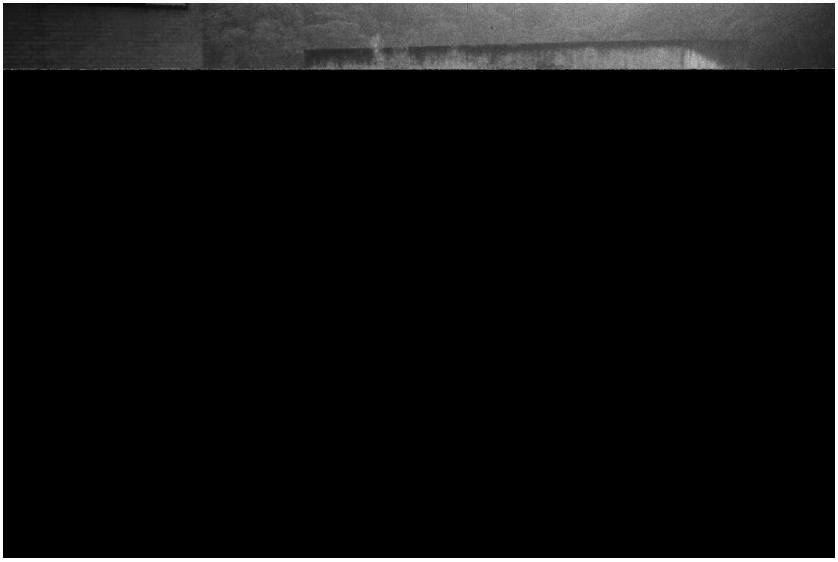

Fig. 2.7. Typical installation of a Dano drum (São Paulo, Brazil).

A Dano drum installed in a developing country is presented in Fig. 2.7.

N.V. Vuilafvoer Maatschappij (VAM) utilized the VAM processing method in the Netherlands starting in 1932 (Weststrate, 1951). VAM was a non-profit utility company formed by the Government for the disposal of city refuse. The processing method essentially was an adaptation of the Indore process for composting large quantities of municipal refuse, which contained little garbage or readily putrescible food materials. In the original process, raw (unground) refuse was placed in long, high piles and turned by overhead cranes. The piles were sprinkled periodically with recirculated leachate from the composting process. The decomposed material was shredded by a hammermill, screened, and sold as humus. In new installations, however, the refuse was first shredded in a special grinder developed by Weststrate (1953), the director of VAM. Recyclable materials were segregated and removed before the shredding began; non-shreddable materials were removed twice a day from the shredder. As the shredded refuse fell through sieve plates, it was picked up on a conveyor belt and transported to an area where it could be readily sprinkled to control the moisture, and turned from time to time to provide aeration during the composting period. The VAM process produced several thousand tons of compost per year from municipal refuse for sale to farmers (Weststrate, 1951). Refuse from The Hague, Groningen, and Zadnvoort was transported in special railway cars to the disposal site at Wijster, where the cars were taken to one of several viaducts 6 m high and 488 m long. At the viaducts, the refuse was discharged in successive mechanically leveled layers below the viaduct and sprinkled with water. The material remained in the piles for up to 8 months for composting, after which the material was pulverized and screened to produce several grades of compost (Weststrate, 1953).

Stovroff and his associates of the Composting Corporation of America (Stovroff, 1954a,b) conducted pilot-plant operations, and studied the financial feasibility of composting municipal and industrial refuse from large communities to produce a soil amendment. The pilot plants incorporated "modern" materials handling equipment designed for the large quantities of refuse generated by the cities. According to the developers of the processes, the mechanization allowed profitable sales of bulk compost at prices below those of stable or barnyard manure. A composting facility was built in Oakland, California, USA as a private enterprise, and was designed to compost 300 tons of mixed waste in an 8-h shift per day, or 600 tons on a two-shift (16 h/day) basis. The operation was entirely aerobic, using the windrow method, and was in effect a modern version of the basic Indore technique.

In London, England, the Borough of Southwark composted street sweepings, market refuse, stable manure, and garbage starting in 1906 (Martin-Leake, 1949). Their method was a modification of the Indore technique using concrete bins of 70 tons capacity. Other efforts were made to utilize organic residues from agriculture (Great Britain, Agricultural Research Council, 1948; Guttridge, 1952; Gothard and Brunt, 1954; Great Britain, Natural Resources, 1954).

In the 1960s, the United States Public Health Service (the predecessor to the United States Environmental Protection Agency) established two demonstration facilities. The facilities were designed to compost MSW mixed with biosolids. One installation was located in Johnson City, Tennessee and the other in Gainesville, Florida (Breidenbach, 1971). The demonstration projects collected information on the technical and financial viability of the process (Wiles, 1975). In addition, research on plant growth and the effect of the application of compost on soil was conducted by the Tennessee Valley Authority and by the University of Florida.

The Metro Waste Conversion System was put into practice for composting MSW in Florida and in Texas, USA. The Metro system used forced aeration through the bottom of the mass in combination with stirring. The stirring was accomplished by means of a traveling endless belt, as shown in Fig. 2.8. In the process, the organic fraction of MSW was placed onto conveyor belts, which distributed the material into elongated bins (as shown in Fig. 2.9). Each bin had perforated bottoms. A set of rails was placed on top of the walls forming the bins. The traveling endless belt moved on the rails. Once a bin was filled, the air flow was activated. Mechanical aeration by means of the belt was conducted once a day. The detention time of the composting material in the bins fluctuated from 1 to 6 days. After the bins, the compost was placed in windrows and allowed to cure.

In 1973, the United States Department of Agriculture (USDA) at the Beltsville (Maryland) Agriculture Research Center started a research program aimed at composting biosolids. Primarily, the US Environmental Protection Agency, the Maryland Environmental Service, and the Washington DC Council of Governments funded the research. In 1975, the research team at Beltsville developed what is now known as the aerated static pile (ASP) method of composting (Epstein et al., 1976). The work at Beltsville included engineering aspects, biological processes, microbiological studies, and plant growth studies (Walker and Willson, 1973; Willson and Walker, 1973; Willson et al., 1980).

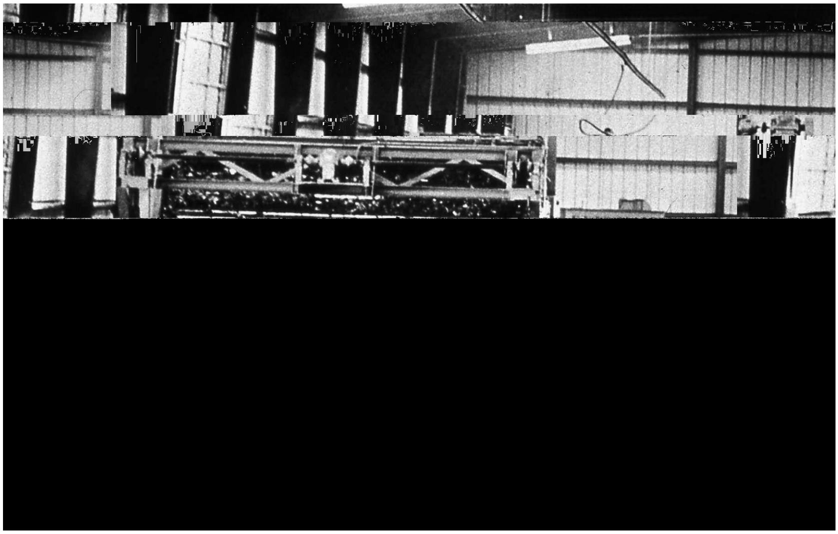

Fig. 2.8. Agitation used by the Metro Waste System (Texas, USA).

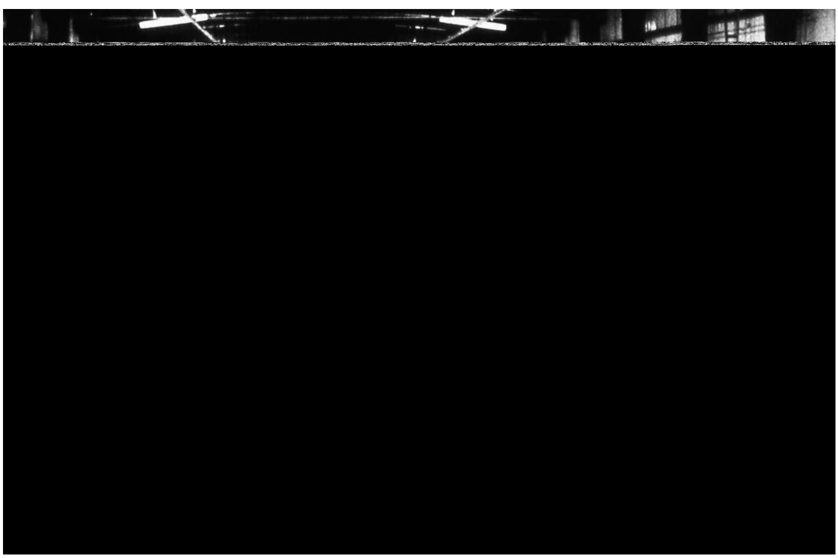

Fig. 2.9. View of bins used by the Metro Waste System (Texas, USA).

In 1975, Rutgers University began several studies on composting of biosolids, both at the University and in Camden, New Jersey. A substantial amount of research was carried out on process engineering, economic analyses, and other aspects of composting (Finstein and Morris, 1975; Finstein et al., 1986, 1987a–d).

In the late 1970s and early 1980s, researchers in Japan carried out work on various aspects associated with the production and use of compost (Yoshida and Kubota, 1979; Chanyasak et al., 1982; Nakasaki et al., 1983).

Essentially at the same time as the work was being conducted in Japan, pioneering research was carried out at the University of Ohio (USA) on plant pathogens and on the use of compost to control plant pathogens (Hoitink et al., 1987; Chen et al., 1988a,b; Hoitink and Schmitthenner, 1988).

The Commission of European Communities, now known as the European Union (EU), has been active for several years in the waste management sector, in particular in the areas of recycling, composting, and energy recovery. The EU has been involved in financing research programs as well as in coordinating research projects. Several different programs dealing with composting have been carried out. Some of these programs include:

- COST 68: Treatment and use of organic sludges and liquid agricultural waste. The project was organized into five working parties: (1) sludge processing; (2) chemical pollution of sludge; (3) biological pollution of sludge; (4) valorization of sludge; and (5) environmental effects of sludge (Alexandre and Ott, 1979; L'Hermite and Ott, 1980, 1983; L'Hermite, 1985, 1990; Dirkzwager and L'Hermite, 1988).
- R&D Program: "Recycling of Urban and Industrial Waste," with particular reference to activities coordinated in the field of composting. Composting comes within the framework of research and development activities into areas of priority concern such as energy, raw material, environment, etc. and was one of the activities coordinated by this program (Zucconi et al., 1983; Gasser, 1985; de Bertoldi and Zucconi, 1986; de Bertoldi et al., 1987; Bidlingmaier and L'Hermite, 1988; Jackson et al., 1992).
- The THERMIE Program was the follow-up to the previous Community Energy Demonstration Program, which was initiated in 1978 and continued up to 1989. The aim of this program was to provide a means of promoting new technologies. With European Community support, many recycling and composting plants were built in Europe, proposing new and advanced technologies. This project was coordinated by Directorate General XVII for Energy (Ferrero, 1996).
- Biomass for Energy and Industry: This Research and Development project, coordinated by Directorate General XII, was mainly dedicated to the recycling of biomass and biowaste with energy recovery. Composting played a prominent role in this project (Grassi et al., 1990).

A considerable amount of work was conducted in Europe (primarily Western Europe) during the 1980s. It is difficult to list all of the important work carried out on biological degradation of organic matter; however, it is very clear that the Commission of European Communities served as catalyst for much of the advance made during this time period (Bidlingmaier et al., 1987; de Bertoldi et al., 1987, 1988, 1996; Stentiford and de Bertoldi, 1988).

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Chapter 3

Microbiology of the Composting Process

H. Insam and M. de Bertoldi

3.1. Introduction

The biological cycling of nutrients is indispensable for life and is mediated through microorganisms. *Biotransformation* is biological modification that alters the chemical structure. The prefix *bio* indicates biotic (living organism) activities (not, for example, the action of UV light or the action of isolated enzymes). Biotransformation may synthesize atoms or simple molecules into more complex molecules (biosynthesis), or vice versa (biodemolition, biodegradation, mineralization). *Biodegradation* is the breakdown of a molecular structure into its elemental components. Biodegradation may be a segmentation of complex into simpler compounds, or even atoms; this segmentation usually is not a simple fragmentation, but often other atoms also are incorporated to form new compounds.

3.2. Definition of Composting (Process) and of Compost (Product)

The presence of mixed organic substrates is a prerogative of composting. More specifically, according to its etymological meaning, *composting* (from the Latin *compositum*, meaning mixture) refers to a biodegradation process of a mixture of substrates carried out by a microbial community composed of various populations in aerobic conditions and in the solid state. Microbial transformation of pure substrates goes under the name of fermentation or biooxidation, but not composting.

The exothermic process produces energy in the form of heat, which results in an increase of the temperature in the mass. A spontaneous process, therefore, passes through a thermophilic phase, which is preceded and followed by two mesophilic phases. During composting there is a temporary release of phytotoxins (intermediary metabolites, ammonia, etc.). At the end of the process, this phytotoxicity is completely overcome and the final product is beneficial to plant growth. The composting process leads to the final production of carbon dioxide, water, minerals, and stabilized organic matter (compost). The process starts with the oxidation of easily degradable organic matter; this first phase is called decomposition. The second phase, stabilization, includes not only the mineralization of slowly degradable molecules, but also includes more complex processes such as the humification of ligno-cellulosic compounds.

From a technical point of view, the composting process is stopped at a phase in which the organic matter still is present in a relatively large quantity (more than 50% of the starting amount); otherwise the process would continue, environmental conditions permitting, until all of the organic components are completely mineralized.

The main product is called compost, which may be defined as the stabilized and sanitized product of composting, compatible and beneficial to plant growth. Compost has undergone: (1) an initial, rapid stage of decomposition; (2) a stage of stabilization; and (3) an incomplete process of humification.

The transformation of fresh organic matter into compost is carried out mainly for three reasons: (1) to overcome the phytotoxicity of fresh non-stabilized organic matter; (2) to reduce the presence of agents (viruses, bacteria, fungi, parasites) that are pathogenic to man, animals, and plants to a level that does not further constitute a health risk; and (3) to produce an organic fertilizer or a soil conditioner, recycling organic wastes and biomass.

Many adjectives have been used for compost; some of them are correct, such as: aerobic, solid state, hygienized, and quality. Some others are in contradiction with the definition of compost and include: anaerobic, fresh, liquid state, etc., and thus should be avoided.

3.3. The Substrates

The decay of materials during composting follows the common biochemical pathways of any other degradation process. Usually, the substrates are biogenic, i.e., they originate from biological activity (e.g., photosynthesis, or consumer biomass). That means, essentially, that all available substrates are either of plant, animal, or microbial origin. Generally, plant materials make up the highest amounts, while animal tissues or microbial components are only minor fractions of any mixture, but usually are the most nutrient-rich fractions. The major natural compounds found in compost substrates are listed in Table 3.1.

3.3.1. Lignin

Lignin is a major structural component of plants, and is the one that is degraded the slowest. The lignin content of wood varies from about 18 to 30%. The number of monomer units is not large, but due to the extraordinary variety of bonding among its basic monomer compounds (derivatives of phenylpropane, mainly coniferyl alcohol), its degradation is very complex. Very often, lignin decomposition is of the co-metabolic type, since energy yield from lignin degradation is negligible.

The degradation of lignin is primarily accomplished by fungi, which are very often pathogens that thrive on the living plant. Lignin-degrading fungi are also known as white-rot fungi, like *Trametes versicolor* (Turkey Tail) or *Stereum hirsutum* (False Turkey Tail). They degrade the lignin and leave the pale-colored cellulose parts. Some fungi, such as *Pleurotus ostreatus*, degrade cellulose and lignin at the same time.

3.3.2. Cellulose

Cellulose is the most abundant component of plants. Cellulose is found in almost every type of organic waste. It is most prominent in wastes that are dominated by plant remains with a high percentage of structural elements (wastes from the wood industry, agricultural waste, and domestic wastes). Cellulose molecules are chains of β-D-glucose with a polymerization degree of 40,000. The glucose molecules are combined by β-1,4-glycosidic bonding. Enzymatic cleavage results from the activity of three enzymes:

1. *Endo-β-1,4-Glucanases* cleave the β-1,4 bonds within the molecule, resulting in long chains with free ends.
2. *Exo-β-1,4-Glucanases* separate the disaccharide cellobiose from the free ends.
3. *Beta-glucosidases* hydrolyze the cellobiose, and the resulting glucose is taken up by the microorganisms.

Table 3.1. Major natural compounds that are the substrates for decomposition

Compound	Composition	Function	P	A	M	Degradability
Lignin	Polymerisates of phenylpropane derivatives, e.g., coniferyl alcohol	Structural compound	3	0	0	Very resistant, mainly by fungi
Cellulose	Glucose $(C_6H_{10}O_5)_n$ polymers: β-1,4 bonds	Structural compound (plant leaves, stems)	3	0	0	Easily, mainly by fungi, but also bacteria, Actinomycetes
Starch	Amylose: linear α-1,4 bonds; Amylopectin: branched α-1,4 bonds	Storage compound in seeds and roots	2	0	1	Good; Aerobically and anaerobically (Clostridium)
Glycogen	α-1,4 and α-1,6 bonds	In animal muscles	0	1	0	Good
Laminarin	β-1,3 bonds	Marine algae (Phaeophyta)	2	0	0	Fair
Paramylon	β-1,3 bonds	Algae (Euglenophyta and Xanthophyta)	1	0	0	Fair
Dextran	1,6 bonds	Capsules or slime layers of bacteria	0	0	1	Fair
Agar	Polymer of Galactose and galacturonic acid	Marine algae (Rhodophyta)	2			Resistant
Suberin, cutine	High polymeric esters of saturated and unsaturated fatty acids	Structural compound	1	0	0	Poor

Hemicelluloses: • Xylan • Araban • Mannan • Galaktan	Low degree of polymerization of sugar monomers (pentoses and hexoses) and uronic acids; usually 20–100 monomers	Cell wall compound, in seeds, straw, wood, algae	3	0	0	Variable degradability, often together with lignin
Pectin	Polymer of galacturonic acids (3×10^4–5×10^5 monomers)	Dissolved, and in the cell wall, in seeds, fruits, and in young wood parts	2	0	0	Easy, by most microorganisms, among them often plant pathogens
Sucrose	Glucose–fructose disaccharide	Vacuoles	2	0	1	Very easy by most microorganisms
Lactose	Glucose–galactose disaccharide	Milk	0	1		Easy by lactic acid bacteria
Hyaluronic acid	Polysaccharide of glucuronic acid and *N*-acetylglucosamine	Connective tissue	0	1	0	Easy
Chlorophyll and other pigments		Plastids	1	0	0	Easy
Alkaloids, tannins	Sugars, mainly alpha-D-glucose	Vacuoles	1		0	Variable
Fats, waxes	Glycerine and fatty acids	Storage compound	1	3	1	Variable
DNS, RNS	Nucleic acids	Nuclei, Mitochondria	1	1	2	Easy
Poly-β-hydroxy butyric acid		Vacuoles, storage compound	0	0	2	Easy
Murein	Peptidoglycan	Cell wall of bacteria	0	0	3	Easy
Chitin	Poly-*N*-acetylglucosamine	Cell wall of fungi; crustacea, insects	0	2	3	Fairly

These materials are found in: plants (P); animals (A); and microorganisms (M). Values indicate the range of relative importance (from 0 — not found to 3 — found in very high quantities).

Under aerobic conditions, many fungi, bacteria, and also myxomycetes are involved in the degradation of cellulose. The catalytic action (mechanical destruction of large structural elements) of the microfauna is considered important. Fungi are, in general, more important for cellulose degradation than bacteria, which is especially the case if the cellulose is encrusted with lignin (e.g., in wood or straw). Since cellulose is rich in C but does not contain N or other essential elements, the mycelial structure of fungi is a competitive advantage. A few fungi to mention are *Chaetomium, Fusarium*, and *Aspergillus*. Among the bacteria, it is mainly the group of myxomycetes or related taxonomic groups (*Cytophaga, Polyangium, Sorangium*). Also, *Pseudomonas* and related genera are known to degrade cellulose, but only few Actinobacteria (formerly called Actinomycetes) are involved.

Under anaerobic conditions, cellulose is mainly degraded by mesophilic and thermophilic *Clostridia*.

3.3.3. Hemicelluloses

Xylan, among the hemicelluloses, is the most important and is found in straw, bagasse (up to 30%), and wood (2–25%). Xylan is made up of pentoses (xylose, arabinose) or hexoses (glucose, mannose, galactose). The degree of polymerization is 30–100. The main degrading enzymes are xylanases, produced by many bacteria and fungi (in some cases, constitutively).

Pectin (polygalacturonides) is made up from unbranched chains of polygalacturonic acid. It is degraded by *pectinase*, which is very common among fungi and bacteria. Many plant pathogens produce pectinases.

Starch is composed of amylose (20%) and amylopectine. Amyloses are unbranched chains of D-glucose (due to 1,4-position β-glycosidic bonding amylose is, in contrast to cellulose, helical). Amylopectin is, in addition, branched at the 1,6 position and contains phosphate residues and Ca and Mg ions. Two types of enzymatic starch degradation are important:

- Phosphorolysis by *phosphorylases*, starting at the free, non-reducing end of the amylose chain, releasing single glucose-1-phosphate molecules. At the 1,6 branches, the enzyme comes to a halt, and only continues after action of *amylo-1,6-glucosidase*.
- Hydrolysis: α-*amylase* cleaves the α-*1,4* bonds within the molecule.

3.3.4. Murein

Murein consists of unbranched chains of N-acetylglucosamine and N-acetylmuramic acid. Muramic acid is bound through lactyl groups to variable amino acids. Murein is the main component of the cell wall of most bacteria.

3.3.5. Chitin

Chitin is, considering the masses, less important than cellulose. Chemically, cellulose and chitin are very similar. While the monomer of cellulose is glucose, the monomer of chitin is *N*-acetylglucosamine. The main difference for degraders is the high concentration of nitrogen in chitin (approximately 7% N, the C/N of chitin is approximately 5).

Many fungi (e.g., *Aspergillus*) and bacteria (e.g., *Flavobacterium, Cytophaga, Pseudomonas*) are able to use chitin as a nitrogen and carbon source. Chitin is degraded through exoenzymes to *N*-acetylglucosamine, which is resorbed, transformed to fructose-6-P, and thus incorporated into the carbohydrate metabolism.

Chitin is the most important structural compound in the cell walls of fungi, and it is the substance that makes up the exoskeleton of insects and crustaceans. In areas with shellfish industry, chitin is an important waste product.

3.4. Composting as a Discontinuous Process

Degradation of organic compounds under natural conditions usually occurs in soils and sediments, on the soil surface, or in water bodies. In most cases, the decomposing substrates have physical contact with the degraded material, or with an external matrix. Thus, an exchange of nutrients of the degrading material and the matrix (e.g., soil, sediment, or water) is usually possible, and due to the dispersal of the degrading material, the decomposition takes place at ambient temperature. There are exceptions to this, for example, the accumulation of leaves during the fall when exothermal processes during decomposition are strong enough to elevate the temperature of the material. Notably, it is mostly human activities that accumulate substrates at a certain place to an extent that allows self-heating, which is a typical feature of any composting process. Since any chemical or biochemical reaction is temperature dependent, many chemical, physical, and biological properties also change during the process (Fig. 3.1).

The present level of understanding of the microbiota involved in composting depends largely on studies made with traditional methods, e.g., isolation and identification of bacteria, including actinobacteria, and fungi (Miller, 1996). Composting induces high metabolic activities of microorganisms at high densities (up to 10^{12} cells g^{-1}). The constant change in conditions (temperature, pH, aeration, moisture, availability of substrates) results in stages of exponential growth and stationary phases of various organisms. The microbial consortia present at any point of time are replaced by others in short intervals. The problem, however, is that despite their viability, only a minor fraction of the microbes can be cultivated.

Biodegradation processes in nature are commonly comparable to a continuous culture (from a microbiological view), and the most important determinant factors are external (substrate quality, temperature, moisture, etc.). Composting, in contrast, resembles a batch culture with steady changes in substrate composition and biochemical conditions. Continuous composting processes may be regarded as a sequence of continuous cultures, each of them with their own physical (e.g., temperature), chemical (the available substrate), and biological (e.g., the microbial community composition) properties and feedback effects. These changes make it difficult to study the process, which virtually is impossible to simulate in the laboratory since temperature, aeration, moisture, etc. are directly related to the surface/volume ratio. However, it is generally accepted that composting is essentially a four-phase process that may be summarized as follows.

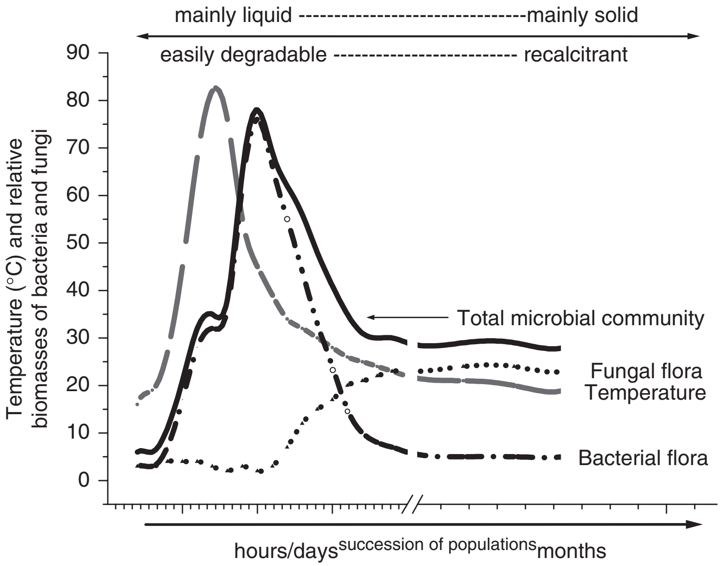

Fig. 3.1. Microbial communities during the composting process: temperature feedback.

3.4.1. Mesophilic Phase (25–40°C)

In this first phase (also called starting phase), energy-rich, easily degradable compounds like sugars and proteins are abundant and are degraded by fungi, actinobacteria, and bacteria, generally referred to as *primary decomposers*. Provided that mechanical influences (like turning) are small, also compost worms, mites, millipedes, and other mesofauna develop, which mainly act as catalysts. Depending on the composting method, the contribution of these animals is either negligible or, as in the special case of vermicomposting, considerable. It has been demonstrated that the number of mesophilic organisms in the original substrate is three orders of magnitude higher than the number of thermophilic organisms, but the activity of primary decomposers induces a temperature rise.

3.4.2. Thermophilic Phase (35–65°C)

Organisms adapted to higher temperatures get a competitive advantage and gradually, and at the end, almost entirely replace the mesophilic flora. Previously flourishing mesophilic organisms die off and are eventually degraded by the succeeding thermophilic organisms, along with the remaining, easily degradable substrate. The decomposition continues to be fast, and accelerates until a temperature of about 62°C is reached. Thermophilic fungi do have growth maxima between 35 and 55°C, while higher temperature usually inhibits fungal growth. Thermotolerant and thermophilic bacteria and actinobacteria are known to

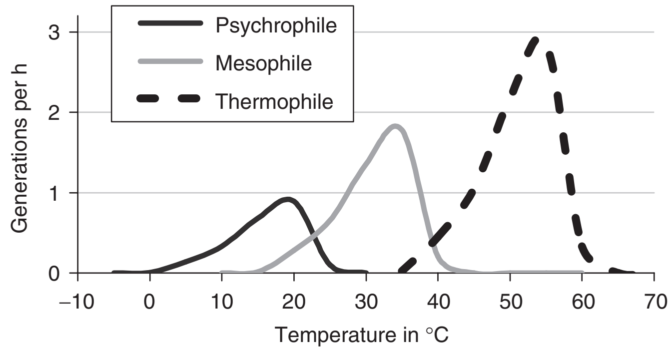

Fig. 3.2. Temperature range of psychrotolerant, mesophilic, and thermophilic organisms, and their generation time.

remain active also at higher temperatures. Despite the destruction of most microorganisms beyond 65°C, the temperature may rise further and may exceed 80°C. It is probable that this final temperature rise is not due to microbial activity, but rather is the effect of abiotic exothermic reactions in which temperature-stable enzymes of actinobacteria might be involved. The temperature range of psychrotolerant, mesophilic, and thermophilic organisms and their generation times are shown in Fig. 3.2.

The same temperatures are not reached in all zones of a compost pile; thus, it is important that, through regular turning, every part of the substrate is moved to the central, hottest part of the pile. From a microbiological point of view, four major zones may be identified within a pile (as shown in Fig. 3.3). The outer zone is the coolest, and well supplied with oxygen; the inner zone is poorly supplied with oxygen; the lower zone is hot,

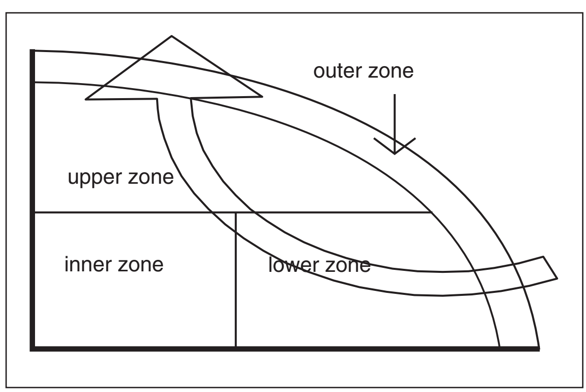

Fig. 3.3. Cross section of a compost windrow (major zones and convection stream are indicated).

and well supplied with oxygen; while the upper zone is the hottest zone, and usually fairly well supplied with oxygen.

The thermophilic phase is important for hygienization. Human and plant pathogens are destroyed; weed seeds and insect larvae are killed. Not only the temperature during the thermophilic phase, but also the presence of a very specific flora dominated by actinobacteria, are important for hygienization through the production of antibiotics. The disadvantage of temperatures exceeding 70°C is that most mesophiles are killed, and thus the recovery is retarded after the temperature peak. This may, however, be avoided by appropriate measures for recolonization.

3.4.3. Cooling Phase (Second Mesophilic Phase)

When the activity of the thermophilic organisms ceases due to exhaustion of substrates, the temperature starts to decrease. Mesophilic organisms recolonize the substrate, either originating from surviving spores, through spread from protected microniches, or from external inoculation. While in the starting phase organisms with the ability to degrade sugars, oligosaccharides and proteins dominate, the second mesophilic phase is characterized by an increasing number of organisms that degrade starch or cellulose. Among them are both bacteria and fungi.

3.4.4. Maturation Phase

During the maturation phase, the quality of the substrate declines, and in several successive steps the composition of the microbial community is entirely altered. Usually, the proportion of fungi increases, while bacterial numbers decline. Compounds that are not further degradable, such as lignin–humus complexes, are formed and become predominant.

3.5. The Microorganisms Involved

3.5.1. Cultivation and Molecular Techniques

Browne (1933) was the first to prove that self-heating of composts is due to biological activity. In the 1930s, Waksman published several papers on the microbiology of composting, and he was the first to publish studies on the population dynamics (Waksman, 1932). Since then, for five decades, isolation and culturing procedures were the basis for studying compost microbial communities (e.g., Finstein and Morris, 1975). It is known from soils and sediments that only a minor fraction ($<1\%$) of microorganisms can be cultured with currently available techniques (Torsvik, 1980). The recently developed approaches based on DNA and RNA have shown that many unknown species of microorganisms are yet to be found in composts (e.g., Beffa et al., 1996). The development of the polymerase chain reaction (PCR) and 16S rRNA sequence analysis have inspired numerous recent studies in environmental microbiology. Blanc et al. (1999) investigated a clone library of bacterial 16S rRNA genes in order to characterize thermophilic communities in hot composts; and Kowalchuk et al. (1999) characterized ammonia-oxidizing bacteria by analyzing rDNA, rRNA, and amoA, the gene encoding a subunit of ammonia monooxygenase. In a recent study, Peters et al. (2000) investigated microbial community successions during composting by means of SSCP (single strand conformation polymorphism) profiles. Alfreider et al. (2002) compared DGGE and SSCP approaches for compost communities, showing that both methods are equally suitable; the two approaches however yielded different community compositions, probably due to the use of different primers for 16s rDNA amplification.

3.5.2. Bacteria

The importance of non-mycelial bacteria during the composting process was long neglected, probably because of the better visibility of fungi and actinobacteria. In some composting processes, e.g., the composting of sewage sludge, bacteria are more important than fungi from the beginning. If temperatures are kept under 60°C, more than 40% of the solids are degraded within the first 7 days, almost entirely through bacterial activity (Strom, 1985). The temperature range from 50 to 65°C is of selective advantage for bacteria, and in particular for the genus *Bacillus*. When temperatures exceeded 65°C, *B. stearothermophilus* often is dominant, almost like in a pure culture.

Most probably, obligate anaerobic bacteria are also common in composts, but so far, very little information is available. During the preparation of *agaricus* substrates, Eicker (1981) found evidence for sulfate reduction under thermophilic conditions.

Actinobacteria

Actinobacteria prefer neutral or slightly alkaline pH and are able to degrade relatively complex substrates. Several are thermotolerant, or even thermophilic, with a temperature range from 50 to 60°C. Most *actinobacteria* grow best when the substrate is moist and the oxygen supply is good. These conditions are usually given when the most easily degradable substrates have already been consumed by bacteria, and when the temperatures rise beyond 45°C. *Actinobacteria* are, however, also well represented in the later consortia.

A special case is the composting of cultivation substrate for *Basidiomycetes*. In this special case, *actinobacterial* growth is especially strong during the second phase. *Actinobacteria* are visible by the naked eye in thick mats, and this phase is called the "firefang" period (temperature around 45°C, relatively low moisture). For the cultivation of *Agaricus*, this *actinobacterial* phase is decisive for the success. It is attempted to maintain a temperature of 48°C throughout the entire substrate (and not only within a certain zone) by regulating humidity and air supply. The main purpose is microbial re-assimilation of ammonium. Overheating of the compost (>70°C) would lead to an irreversible alteration of the material, and ammonia would be released.

Thermus/Deinococcus Group

Members of the *Thermus/Deinococcus* group grow on organic substrates at temperatures from 40 to 80°C, with optimum growth between 65 and 75°C. The numbers in biowaste composts were as high as 10^7–10^{10} g^{-1} dry weight of compost (Beffa et al., 1996). Thus, it seems that *Thermus* species, previously known only from geothermal sites, have probably adapted to the hot-compost system and play a major role in the peak-heating phase. Also, a number of autotrophic bacteria were isolated from composts. These non-sporing bacteria grew at 60–80°C, with optima of 70–75°C, and closely resembled *Hydrogenobacter* strains that previously were known only from geothermal sites. They obtain their energy by oxidizing sulfur or hydrogen, and synthesize their organic matter from CO_2 (Beffa et al., 1996).

An overview of bacteria that have been found to be involved in composting is given in Table 3.2.

Table 3.2. Overview of bacteria that have been found to be involved in composting processes[1]

Phylogenetic group	Genus species	Ecological relevance	Succession stage	Reference
Proteobacteria Alpha	*Pseudomonas putida* strain ATCC 11172	Pathogenic		Alfreider et al. (2002)
	Pseudomonas sp.			Miller (1996)
	Methylosinus trichosporium	Methanotrophic		Murrell et al. (1998)
	Caulobacter spp.		Early	Michel et al. (2002)
	Erythrobacter longus		Early	Michel et al. (2002)
Beta	*Nitrosospira briensis*	Nitrifier		Murell et al. (1998), Kowalchuk et al. (1999)
	Nitrosomonas europaea	Nitrifier		Murell et al. (1998), Kowalchuk et al. (1999)
	Nitrosolobus multiformis	Nitrifier	Middle	Michel et al. (2002)
Gamma	*Escherichia coli*	Potential pathogen		Lott Fischer (1998)
	Methylomonas methanica	Methanotroph		Murrell et al. (1998)
	Azotobacter chroococcum	N-fixer	Late	Bess (1999)
	Salmonella sp.	Pathogenic		Lott Fischer (1998)
	Streptomyces rectus			Miller (1996)
	S. thermofusus			Miller (1996)
	S. violaceus-ruber			Miller (1996)
	S. thermoviolaceus			Miller (1996)
	Streptomyces sp.			Miller (1996)
	Nocardia sp.			Miller (1996)
	Microbispora bispora		Thermophilic	Miller (1996)
	Actinomadura sp.		Thermophilic	Degli-Innocenti et al. (2002)

Table 3.2. Overview of bacteria that have been found to be involved in composting processes[1] — *Cont'd*

Phylogenetic group		Genus species	Ecological relevance	Succession stage	Reference
Gram-positive bacteria	Endospore-forming, low GC	*Bacillus stearothermophilus*	Classic thermophilic bacterium in composts		Various
		B. thermodenitrificans	Thermophilic, denitrifier		Blanc et al. (1997)
		B. brevis			Miller (1996)
		B. circulans			
		B. coagulans			
		B. sphaericus			
		B. subtilis			
		B. licheniformis			
		Bacillus sp.	Potential pathogen		Lott Fischer (1998)
		Clostridium thermocellum			
		Clostridium spp.	Some are N-fixers	Anaerobic	de Bertoldi et al. (1983)
		Klebsiella sp.	N-fixation		de Bertoldi et al. (1983)
	Actinomycetes	*Saccharomonospora viridis*	Pathogenic		Lott Fischer (1998)
		Streptomyces thermovulgaris	Pathogenic	Thermophilic	
		Actinobifida chromogena			Miller (1996)
		Thermoactinomyces vulgaris		Thermophilic	Miller (1996)
		Micropolyspora faeni			Miller (1996)
		Pseudonocardia thermophila			Miller (1996)
		Thermomonospora curvata			Miller (1996)
		Th. viridis			
		Th. sacchari			
Deinococcus/ Thermus group		*Thermus* sp.		Thermophilic	Beffa et al. (1996)
		Hydrogenobacter			

[1]Comprehensive compilation of microorganisms in compost may be found in Ryckeboer et al. (2003).

3.5.3. Archaea

Many archaea are known to be thermophilic or even hyperthermophilic. They have primarily been isolated from hypothermal vents. Only in a few cases, archaea have been isolated from composts (e.g., Stackebrandt et al., 1997), but since considerable methanogenesis in compost piles has recently been reported (Cabanas-Vargas and Stentiford, 2006), it is likely that methanogenic archaea may be found if specifically searched for. The reason for the relatively low abundance of archaea probably is that they are usually oligotrophic, and their generation times are much higher than those of bacteria, which make them unsuited to rapidly changing conditions.

3.5.4. Fungi

During the starting phase, fungi compete with bacteria for the easily available substrates. Since the maximum specific growth rates of bacteria exceed that of fungi by one order of magnitude (Griffin, 1985), fungi are very soon out-competed. Also, a good supply of oxygen is more important for fungi than for bacteria, and even in force-aerated systems, temporary anoxic conditions may occur. For these reasons, but also because of the lower thermotolerance, fungi play a negligible role during the thermophilic phase. One exception is the composting of substrates that are particularly rich in cellulose and in lignin. In that case, fungi remain most important throughout the entire process. In the later phases of composting, the water potential decreases, which is an advantage for fungi. A summary of fungi that have been found in composting is given in Table 3.3.

3.6. Carbon and Nitrogen Balance

During composting, organic matter follows different metabolic pathways: mineralization, humification, and partial degradation (by aerobic respiration, anaerobic respiration, and fermentation).

In a well-managed process, about 50% of the biodegradable organic matter is converted into CO_2, H_2O, mineral salts, and energy. In the remaining organic matter: about 20% undergoes complex metabolic transformations, with the final production of humic-like substances; the other 30% is partially degraded by aerobic and anaerobic processes with the final production of less-complex organic molecules. This loss of biodegradable organic matter during the composting process may vary from 30 to 60%. The factors affecting this variation are: system of composting, length of the process, aeration system, quality (chemical and physical) of the organic matter, particle size, C/N, and temperature pattern.

All of the microbial transformations of nitrogen occurring in nature also take place during composting, even if with different significance. In composting, the most important phases are mineralization, nitrification, and assimilation. Reductive assimilation of nitrate and the following conversion to organic nitrogen compounds, inside the microbial cells, are important steps in the composting process, in order to reduce nitrogen losses in compost and in soil.

Table 3.3. Fungi that have been found during the composting processes

Phylogenetic group	Genus species	Ecological relevance	Succession stage	Reference
Zygomycetes	*Mortierella turficola*	Decomposer		Miller (1996)
	Mucor miehei	Zymogenous	Early	Miller (1996), de Bertoldi et al. (1983)
	M. pusillus		Thermophilic	
	Rhizomucor pusillus	20–55°C, typical early colonizer, exploiting simple sugars, amino acids, etc.; inactivated during peak-heating, and it does not recolonize afterwards		
	Rhizomucor sp.			Miller (1996)
Ascomycetes	*Chaetomium elatum*	Soil inhabitant	Early and late	Ivors et al. (2002)
	Chaetomium thermophilum	Decomposer	Thermophilic	Miller (1996)
	Dactylomyces crustaceus			Miller (1996)
	Aporothielavia leptoderma			Ivors et al. (2002)
	Thermoascus aurantiacus		Thermophilic	Miller (1996)
	Thielavia thermophilia			Miller (1996)
Basidiomycetes	*Armillaria mellea*	Cellulolytic and ligninolytic	Mesophilic	de Bertoldi et al. (1983)
	Clitopilus insitus			
	Pleurotus ostreatus			
	Lentinus lepideus			
	Fomes sp.			
	Coprinus sp., *C. cinereus*	Coprophagous	Early	Miller (1996), de Bertoldi et al. (1983)
	Lenzites sp., *L. trabea*			

(*continued*)

Table 3.3. Fungi that have been found during the composting processes — *Cont'd*

Phylogenetic group	Genus species	Ecological relevance	Succession stage	Reference
Mitosporic fungi	*Aspergillus fumigatus*	Wood decaying	Mesophilic and thermophilic	Miller (1996), de Bertoldi et al. (1983)
	Humicola insolens	Potential pathogenic, allergenic, heterotrophic	Early and late, thermophilic	Lott Fischer (1998), de Bertoldi et al. (1983)
	Thermomyces lanuginosus		Thermophilic	http://helios.bto.ed.ac.uk/bto/microbes/
	Paecilomyces sp.	Cellulolytic		de Bertoldi et al. (1983)
	Scopulariopsis brevicaulis	Cellulolytic		de Bertoldi et al. (1983)

Nitrogen fixation and denitrification are anaerobic events that can occur during composting but, in any case, at low rates. In composting, total nitrogen content decreases during the course of the process, mainly by ammonia volatilization. However, the C/N decreases during the process because of the even higher loss of carbon compounds (mainly as CO_2). The total content of nitrogen in the starting material also influences the rate of volatilization.

The mineralization of nitrogenous organic compounds leads to the production of free ammonia that, if not immediately oxidized by nitrifying bacteria, can be lost to the environment through volatilization. Additional nitrogen loss during composting can be caused by denitrification, an anaerobic microbial process that reduces nitrate to N_2. This process can occur only in anaerobic niches, which are always also present in well-oxygenated material. Some denitrifying bacteria can operate also in thermophilic conditions at 65°C (*Bacillus* sp.), others at mesophilic temperatures (*Pseudomonas, Paracoccus*). To what extent anaerobic ammonia oxidation (Anamox) is of importance in composts is not known, but it may be important when it comes to the evaluation of the greenhouse gas potential of composting.

Despite these nitrogen losses, partial recovery takes place later in the process, due to the activity of nitrogen-fixing bacteria. Many species have been isolated during composting, mainly associated with the mesophilic stage: *Azospirillum, Klebsiella, Enterobacter, Bacillus, Clostridium* (de Bertoldi et al., 1982, 1983). Biological nitrogen fixation is inhibited by the presence of ammonia and by high temperature. Therefore, nitrogenase activity is higher during the later phases of decomposition.

During the first stage of composting, autotrophic nitrification is strongly inhibited by high temperatures, pH, and ammonia concentration. Ammonium oxidizing bacteria are the most inhibited (*Nitrobacter*) (Loehr, 1974; Focht and Chang, 1975). Heterotrophic nitrification, operated by other bacteria (*Arthrobacter*, *Actinomyces*) and by *eumycetes* (*Aspergillus flavus, Penicillium*), seem to be less conditioned by these factors. Indeed, the production of nitrate in the early phases of composting seems mostly exclusively the work of heterotrophic nitrifying microorganisms (Eylar and Schmidt, 1959; Hora and Iyengar, 1960; Hirsch et al., 1961; Marshall and Alexander, 1962; Alexander, 1977).

These heterotrophic nitrifying microorganisms and those that directly assimilate ammonia for their anabolic metabolism are the most important agents in reducing the negative effects of ammonia volatilization. The importance of this event is double: to reduce ammonia pollution of the atmosphere and to limit nitrogen loss in compost.

3.7. Advanced Microbiological Analyses for Maturity Determination

It is difficult to determine the stability and maturity of a particular sample of compost by visual analysis, or any single analytical parameter. Compost that no longer is undergoing rapid decomposition and whose nutrients are strongly bound is termed *stable*; unstable compost, in contrast, may either release nutrients into the soil due to further decomposition, or it may tie up nitrogen from the soil. Compost that is not fully stable can be useful in certain situations, e.g., when a direct and rapid nitrogen supply is desired. The term *mature* refers to the degree of phytotoxicity of a compost. Immature compost will contain more growth-inhibiting compounds than mature compost.

Traditional compost analysis has focused on NPK and micronutrient concentrations in an effort to mirror fertilizer analysis. Compost, however, is much more complex than fertilizer, and its most significant value for the plants may be far more than its mineral contribution to the soil. Its microbiological component determines how the compost will perform as a soil inoculant and plant disease suppressant.

However, the control of compost quality and maturity today is not much different than what it was 20 years ago: a few chemical parameters like pH, ammonia, and C/N were regularly used, as well as plant growth and germination tests (e.g., Amlinger, 1993; Itävaara et al., 1997). Concise compost maturity and quality criteria still are lacking, and usually do not include microbiological aspects, despite the fact that microbial activity is the major process for compost production and utilization. Rather than single chemical quality parameters or the response of one or two plant species in germination tests, microbiological tests may provide information on a multitude of features of the compost material. Some microbiological tests for assessing compost maturity and quality are given in the following sections.

3.7.1. Prerequisites for Proper Analysis

Since composting is a biological process, degradation will also go on after sampling. For this reason, sample storage is an important issue, less so for the chemical tests, but certainly for the biological assays. Care must be taken that the storage conditions do not alter the microbiological test results. Essentially, we have two options: first, the sample should be placed in an insulated container that allows some exchange of oxygen. This type of storage can be used if the sample is analyzed within 24 h. This type of container ensures that the original temperature of the compost is maintained, and thermophilic organisms are not replaced by a mesophilic community. If storage longer than 24 h is necessary, refrigeration to 2°C has been recommended. However, some precautions must be followed. In another section of this book, information is given on the methods for proper sample collection for obtaining reliable and representative results. A study by Butler et al. (1999) obtained potentially useful information about biosolids compost age and storage time interactions on the three variables tested. Response plots can assist the researcher in determining how long samples may be stored before being affected by refrigerated storage. In general, very young biosolids compost samples were found to be unaffected by refrigerated storage of up to 11 weeks, while samples greater than 2-weeks old were affected by storage of as little as 2 weeks. While any microbiological method that employs living cells is dependent on recovery after storage, molecular biological methods using drying at room temperature also appears to be appropriate.

3.7.2. Isolation of Microorganisms

A standard analysis for microbiological content in compost is determined by the concentration of six functional groups of microorganisms: aerobic bacteria, anaerobic bacteria, fungi, actinobacteria, pseudomonads, and nitrogen-fixing bacteria (Bess, 1999). Currently, there are procedures to evaluate the concentrations of these organisms in finished compost; however, more research is needed to acquire the necessary baseline data for a reliable maturity index.

3.7.3. Heat Evolution

A very simple and rapid means to evaluate compost maturity is to determine its temperature. In general, in moderate climates, if the temperature of the compost is more than 8°C higher than the ambient air, the compost is still fairly unstable.

The self-heating test in Dewar flasks, as first proposed by Niese (1963), is a frequently used test. The principle is the self-heating potential of biodegrading organic material through (micro)biological activity. A slow or no rise in temperature indicates a high degree of maturation. In the test, a 2-L Dewar flask is filled with compost and a thermometer or a temperature sensor is placed in the upper third of the container. The maximum temperature is registered during a period of up to 10 days, and the result is transformed into decomposition classes (also known as Rottegrad or degree of decomposition; see Table 3.4). The Dewar flask self-heating test is considered a very robust test and in a comparative study, it was the most sensitive indicator of compost maturity. This test showed changes throughout the 57-day biosolids composting period evaluated.

3.7.4. Respiration

Biodegradable material is degraded throughout the composting process. Microbial degradation under aerobic conditions is called respiration (organic matter is converted into water, CO_2, inorganic compounds, and humic matter). The respiratory activity is directly related to the endogenous supply of degradable material. The determination of respiratory activity may either be a determination of O_2 consumption or CO_2 production.

Table 3.4. Degrees of decomposition (rottegrad) by the self-heating test (Itävaara et al., 1997)

Rise in temperature (°C)	Degree of decomposition	Description
>40°C	I	Raw refuse, very slight decomposition
30–40°C	II	Slight decomposition
20–30°C	II	Medium decomposition
10–20°C	IV	Good decomposition
0–10°C	V	Decomposition advanced or completely finished

Table 3.5. Compost maturity tests based on respiration

Method	Principle	Procedure	Reference
Jar method	CO_2 production, 1–4 days incubation, discontinuous	Compost is placed in air-tight jars where CO_2 is trapped in an alkaline solution which is then titrated; simple and cheap	Isermeyer (1952)
IR-gas analysis	CO_2 production, continuous	Through-flow measurement device, high accuracy	Heinemeyer et al. (1989)
Electrolytic respirometer	O_2 consumption continuous		Usui et al. (1985)
Solvita® test	Gel technology in which respiration gases from composts are quantified by colorimetry. Besides CO_2, the test also includes ammonia measurement		Seekins (1996)

The rate of oxygen utilization represents the extent of biological activity. For horticultural applications, <20 mg O_2 kg^{-1} compost dry solids h^{-1} is considered stable. For field applications, <100 mg O_2 kg^{-1} compost dry solids h^{-1} is considered sufficiently mature. The Solvita test, available from Woods End Laboratories, is a quick test for respiration rate and also measures ammonia content. Less than 5 mg CO_2 — carbon g^{-1} compost carbon day^{-1} — is considered stable and is usually suitable for seeding. Values exceeding 20 mg CO_2 — carbon g^{-1} compost carbon day^{-1} — indicate instability of the compost. Results, however, must be interpreted carefully since composts that are cold, dry, or very salty may not respire even though they are not stable.

A listing of maturity tests based on respiration is presented in Table 3.5.

3.7.5. Community-Level Physiological Profiling (CLPP)

This method has recently been proposed for compost maturity testing (Insam et al., 1996; Lulu et al., 2001). The principle is that compost extracts are inoculated onto microtiter plates that contain 31 different C substrates. The utilization pattern of these substrates indicates if the compost is mature or not (Lulu et al., 2001).

3.7.6. Enzyme Activity Tests

Several enzymes, among them *reductase*, *endo-cellulase*, *glucosidase*, *lipase*, *phosphatase*, *dehydrogenase*, and *arginine ammonification*, have been proposed for the purpose of maturity testing (Itävaara et al., 1997). However, none of these methods has, so far, been successful in practice.

3.7.7. Outlook Toward New Maturity Test Methods

Community-based methods based on DNA analysis are becoming standard in microbial ecology (Torsvik et al., 1990; Gottschal et al., 1997), and also in the analysis of compost communities. Remarkable advances have been made during the last few years in the field of community analysis based on DNA (Leij and VanderGheynst, 2000; Ohno et al., 2000). Many compost microorganisms have been detected with molecular-based methods that had not been detected with classic isolation procedures. One day, key species may be available that indicate compost maturity. DNA microarrays represent a revolutionary advance in molecular ecology. The core innovation of the microarray technique is the ability to attach nucleic acids to a solid matrix in a precise location, e.g., on a glass slide, to create a densely packed array. DNA chip technology offers the possibility to screen for the presence or absence of hundreds or even thousands of microbial species in environmental samples (Guschin et al., 1997; Ogram, 2000). Specific compost-targeted microarrays are suitable to investigate bacterial (Franke-Whittle et al., 2005, 2006) and fungal community patterns (Hultman et al., 2006), including general "decomposers," as well as plant growth promoting organisms and plant and human pathogens.

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Chapter 4

Factors that Affect the Process

L.F. Diaz and G.M. Savage

4.1. Substrates

In composting, the substrate is the waste to be composted; and similar to any other biological process, the chemical and physical characteristics of the substrate are critical in the viability of the process (in terms of course and rate). Essentially, it is the availability of the nutrients to the microorganisms and the concentration and balance of the nutrients that dictate the feasibility of the composting process. Some of the most important physical characteristics of the substrate are primarily related to particle size and moisture content of the material. Some of the pertinent chemical characteristics include those associated with molecular size, complexity and nature, as well as elemental makeup of the molecules.

The complexity and nature of the molecular structure of the substrate are particularly important because these characteristics define the assimilability of the nutrients by the various microorganisms. The capacity of a microorganism to assimilate a particular substrate is a function of the microorganism's ability to synthesize the enzymes responsible for breaking down complex compounds. The complex compounds are broken down into intermediate compounds or into an element that can be utilized by the microorganism in its metabolism and synthesis of new cellular material. In the event that all of the microbes do not have the necessary enzymes, the substrate basically remains in its original form.

Therefore, the discussion on nutrients that follows should be interpreted in that light. The waste should contain all necessary nutrients. Only rarely must or should chemical nutrients be added.

4.1.1. Types and Sources of Nutrients

The macronutrients for microbes are carbon (C), nitrogen (N), phosphorous (P), and potassium (K). Among the micronutrients are cobalt (Co), manganese (Mn), magnesium (Mg), copper (Cu), and a number of other elements. Calcium (Ca) falls somewhere between the macro and the micronutrients. However, the principal role of Ca probably is as a buffer, i.e., to resist change in pH level.

Even though nutrients may be present in sufficiently large concentrations in a substrate, they are unavailable to the microbes unless they are in a form that can be assimilated by the microbes and thereby become available to them. (The situation is analogous to that of cellulose in human nutrition, in that, the carbon in cellulose is of no nutritional value to a person who might chance to ingest a cellulosic material, such as paper.)

An important point to remember is that availability is a function of the enzymatic makeup of the individual microbe. Thus, certain groups of microbes have an enzymatic complex that permits them to attack, degrade, and utilize the organic matter as found in a freshly generated waste; whereas, others can utilize only the decomposition products (intermediates) as a source of nutrients. The significance of this fact is that the decomposition and, hence, the composting of a waste is the result of the activities of a dynamic succession of different groups of microorganisms in which one group, so to speak, prepares the way for its successor group.

Another important aspect of nutrient availability in composting is that certain organic molecules are very resistant, i.e., refractory to microbial attack, even to microbes that possess the required enzymatic complex. The consequence is that such materials are broken down slowly, even with all other environmental conditions maintained at an optimum level. As discussed in a previous chapter, common examples of such materials are lignin (wood) and chitin (feathers, shellfish, exoskeletons). Cellulose-C is unavailable to the majority of the microbes, although it is readily available to certain fungi. Nitrogen is easily available when in the proteinaceous, peptide, or amino acid form; whereas the minute amounts present in chitin and lignin are difficultly available. Sugars and starches are readily decomposed, and fats are somewhat less so.

4.1.2. C/N

One of the most important aspects of the total nutrient balance is the ratio of organic carbon to total nitrogen (C/N). A C/N in the starting material of about 25–30 is optimum for most types of wastes.

Living microorganisms in their metabolism utilize about 30 parts of carbon for each part of nitrogen. About 20 parts of carbon are oxidized to CO_2 (ATP), and 10 parts are utilized to synthesize protoplasm. Indeed, the average C/N in many bacteria is about 9–10.

If the amount of carbon over that of nitrogen is too great (high C/N), biological activity diminishes. In a composting operation, the manifestation could require an excessively long time to reduce the C/N to a more suitable level (Golueke, 1977). The optimum C/N is, to some extent, a function of the nature of the wastes, especially of the carbonaceous components. If the carbon is bound in compounds broken down with difficulty by biological attack, its carbon accordingly would only become slowly available to the microbes. Compounds of this sort are chiefly lignin, some aromatics, and some physical forms of cellulose.

The only observable penalty for having a C/N lower than 20 is the loss of nitrogen through ammonia volatilization. This process is enhanced by high temperatures and basic pH (about 8–9). This loss occurs at the starting of the process during the thermophilic phase, in particular, when the material is turned in a windrow or tumbled in a reactor. Generally, the outer layer of material of an undisturbed windrow prevents the ammonia from escaping from the pile. Loss of ammonia, besides producing odors and polluting the atmosphere, reduces the nitrogen content of the final product, also limiting the value of the organic fertilizer produced.

In a well-conducted process, the C/N decreases constantly. This is due to the biological mineralization of carbon compounds and loss as CO_2.

If a compost has a high C/N and decomposes rapidly in the soil, it can rob the soil of the nitrogen needed to support plant growth. If the compost has too low a C/N, the ammonia released can be phytotoxic to plant roots (Zucconi et al., 1981a,b).

With respect to the nutritional needs of the microbes active in composting, the C/N of the waste to be composted is the most important factor that requires attention. Experience shows that, almost without exception, all other nutrients are present in typical organic waste in adequate amounts and ratios.

Requirements with respect to the C/N are functions of the relative differences in amounts of the two elements used by the microbes in metabolism to obtain energy and in the synthesis of new cellular material. A large percentage of the carbon is oxidized to carbon dioxide by the microbes in their metabolic activities. The remaining carbon is converted into cell wall or membrane, protoplasm, and storage products. The major consumption of nitrogen is in the synthesis of protoplasm. Consequently, much more carbon than nitrogen is required. Departures from a C/N of 25/1 to 30/1 lead to a slowing of decomposition and hence of composting. On the other hand, chances are good that nitrogen will be lost as ammonia-N if the C/N is lower than those levels. The reason for the loss is that nitrogen in excess of the microbial needs is converted by the organisms into ammonia. A combination of high pH level and elevated temperature very likely leads to volatilization of the ammonia.

If the C/N of a waste is too high, it can be lowered by adding a nitrogenous waste. Conversely, if the C/N is too low, a carbonaceous waste can be added. The nitrogen content and the C/N of various wastes and residues are listed in Table 4.1. Additional information is presented in other chapters.

The nitrogen content of a waste can be determined by means of the standard Kjeldahl method. The determination of the carbon content is not as readily done because it is difficult to obtain a representative sample, the required analytical equipment is expensive, and an appreciable skill on the part of the analyst is demanded. Fortunately, an estimate of the carbon can be made that suffices for the purpose of composting. It is based on a formula developed in the 1950s by New Zealand researchers (Anonymous, 1951). It is as follows:

$$\text{Percent carbon} = \frac{100 - \text{percent ash}}{1.8}$$

Studies have shown that values obtained according to the formula approximate those from more accurate laboratory studies within 2–10%. In small-scale composting in which

Table 4.1. Nitrogen content and C/N of various wastes (Golueke, 1977)

Material	Nitrogen	C/N
Activated sludge	5	6
Animal tankage	–	4.1
Blood	10–14	3.0
Cow manure	1.7	18
Digested sewage sludge	2–4	–
Grass clippings	3–6	12–15
Horse manure	2.3	25
Mixed grasses	214	19
Nightsoil	5.5–6.5	6–10
Non-legume vegetable wastes	2.5–4	11–12
Pig manure	3.8	–
Potato tops	1.5	25
Poultry manure	6.3	15
Raw sewage sludge	4–7	11
Sawdust	0.1	200–500
Sheep manure	3.8	–
Straw, oats	1.1	48
Straw, wheat	0.3–0.5	128–150
Urine	15–18	0.8

nitrogen and carbon analyses may not be financially feasible, it can be assumed that the C/N will at least approach the proper level if the ratio of green (in color) fresh waste (or of food preparation wastes, or of fresh manure) to dry, non-green waste is volumetrically about 1:4.

4.2. Environmental Factors

Because composting is a biological process, it is fundamentally affected by the collection of environmental factors that determine the course of action in all biological systems. The principal environmental factors of interest in composting are temperature, pH, aeration, moisture, and substrate (i.e., availability of essential nutrients). Since the substrate was discussed in the preceding paragraphs, it will receive no further attention in this section. These factors collectively determine rate and extent of decomposition. Obviously, the closer they collectively approach optimum levels, the more rapid will be the rate of composting. Despite the use of the term "collectively," the closest to which a given process can approach its maximum potential rate is determined by the factor that is farthest removed from being at an optimum level. The factor which places the uppermost limit is appropriately known as the "limiting factor."

4.2.1. Temperature

Composting is a bio-oxidative microbial degradation process of mixed organic matter. This exothermic process produces a relatively large quantity of energy. Only 40–50% of this energy can be utilized by microorganisms to synthesize ATP; the remaining energy is lost as heat in the mass. This large amount of heat causes an increase of temperature in the mass and can reach temperatures of the order of 70–90°C. Finstein calls this process "microbial suicide" (Finstein et al., 1980). Indeed, high temperatures inhibit microbial growth, slowing the biodegradation of organic matter. Only few species of thermophilic bacteria show metabolic activity above 70°C. To have a high rate of biodegradation and a maximum microbial diversity, the temperature must range between 30 and 45°C (de Bertoldi et al., 1983; Finstein et al., 1983; Stentiford, 1993). During the composting process, in order to minimize the retention time, a feedback temperature control can be operated with a set point between 30 and 45°C.

However, in a composting process, the thermophilic phase should not be totally eliminated because it is the most important phase in reducing pathogenic agents. Furthermore, the thermophilic phase must be maintained at the starting of the process, when the availability of readily degradable molecules allows temperatures to reach 70°C.

In forced-aeration systems, the dominant heat-removal mechanism is evaporative cooling (vaporization of water), which accounts for perhaps 80–90% of the heat removal. In such systems, the contribution of conduction to heat removal may be small (Finstein et al., 1999).

Part of the heat produced during composting in a closed reactor can be recovered and transformed by a heat pump to produce hot water both for domestic and for industrial heating (Jaccard et al., 1993).

4.2.2. Hydrogen Ion Level (pH)

Generally, organic matter with a wide range of pH (from 3 to 11) can be composted (de Bertoldi et al., 1985). However, the optimum range is between 5.5 and 8.0. Whereas bacteria prefer a nearly neutral pH, fungi develop better in a fairly acidic environment.

In practice, the pH level in a composting mass cannot be changed easily. Generally, the pH begins to drop at the beginning of the process (i.e., down to 5.0) as a consequence of the activity of acid-forming bacteria that break down complex carbonaceous material to organic acids as intermediate products. When this acidification phase is over and the intermediate metabolites are completely mineralized, the pH tends to increase and at the end of the process is around 8.0–8.5.

High pH values in the starting material in association with high temperatures can cause a loss of nitrogen through the volatilization of ammonia. Whereas in anaerobic digestion, the critical pH level generally covers a fairly narrow range (e.g., 6.5–7.5), the range in composting is so broad that difficulties due to an excessively high or low pH level are rarely encountered.

Because it is unlikely that the pH will drop to inhibitory levels, there is no need to buffer the composting mass by adding lime (calcium hydroxide). Indeed, the addition of lime should be avoided because it can lead to a loss in ammonium nitrogen in the later stages of composting that exceeds the normal loss. An exception could be in the composting of fruit wastes. With such wastes, the pH can drop to 4.5. There is some evidence that under such circumstances, the composting process can be accelerated (National Canners Association Research Foundation, 1964). At the relatively elevated temperatures and pH levels that occur as composting progresses, the ammonium ion is volatilized and the resulting ammonia gas is lost during the aeration of the composting mass. Although some loss of ammonia almost always occurs in aerobic composting, the loss is aggravated by the presence of lime. However, the lime does improve the physical condition of the composting wastes, perhaps partly by serving as a moisture absorbent.

4.2.3. Aeration

In composting, one of the main factors that can be most influenced by technology and around which system designs are developed is the provision of oxygen to the composting mass. The air contained in the interspaces of the composting mass, during the microbial oxidative activity, varies in composition. The carbon dioxide content gradually increases and the oxygen level falls. The average CO_2 plus O_2 content inside the mass is about 20%. Oxygen concentration varies from 15 to 20% and carbon dioxide from 0.5 to 5% (MacGregor et al., 1981). When the oxygen level falls below this range, anaerobic microorganisms begin to exceed aerobic ones. Fermentation and anaerobic respiration processes take over. It is, therefore, important that microorganisms have a constant supply of oxygen to maintain their metabolic activities unaltered. After a few hours of composting, the oxygen level drops to very low levels and oxygen has to be supplied by ventilation. Periodic pile turning, every one or two days, without any ventilation of the mass, cannot guarantee a constant level of oxygen inside the mass.

Normally, oxygen is made available to the mass through ventilation (positive or negative pressure or both systems in conjunction). Ventilation, besides providing oxygen to the mass, serves other functions such as temperature and moisture control. In a composting pile at 60°C, the amount of air needed to control temperature and to replenish the O_2 consumed is in the ratio of 9:1 (air function ratio). At lower temperatures, this ratio increases (Finstein et al., 1986, 1987, 1999; Finstein and Hogan, 1993). The ventilation process should, therefore, be managed to supply sufficient oxygen for aerobic respiration (which, in turn, promotes heat generation) while performing associated heat removal. A satisfactory solution is to ventilate the mass at a specific rate such that de-oxygenation is avoided. A suggested first approximation is 0.15 m^3 air per wet metric ton of mass per minute. To control temperature, a feedback temperature should work in conjunction with a pre-selected set point.

The determination of the amount of air required to ensure aerobiosis in a composting mass has been and is the goal of many researchers. The attainment of that goal is made exceedingly difficult by the fact that it cannot be done by the methods of analysis developed over the years for wastewater.

One of the earlier investigations was carried on by Schulze (1960, 1964). Using a rotating drum as a reactor, he forced air through the drum at a given rate and measured the oxygen in the exiting air. Although Schulze's approach did not lead to a determination of the total oxygen demand of the material, it did give an indication of the rate of oxygen uptake. He found the respiratory quotient to be one that is:

$$\frac{\text{carbon dioxide produced}}{\text{oxygen consumed}} = 1.0$$

In attempts to relate oxygen uptake to level of certain key environmental factors, Schulze found that qualitatively, the closer the environmental conditions approached an optimum level, the greater were the rate and amount of oxygen uptake. Thus, he reports that the oxygen uptake increased from 1 mg/g volatile matter at 30°C to 5 mg/g volatile matter at 63°C (Schulze, 1960, 1964; Regan and Jeris, 1970; Golueke, 1972). Conversely, oxygen uptake became less as environmental conditions worsened. The variability of results, a reflection of the variability of the composition of solid wastes, is illustrated by those obtained by Chrometzka (1968) and Lossin (1971). Chrometzka (1968) reports oxygen requirements that range from 9 mm^3/g/h for mature compost to 284 mm^3/g/h with fresh compost. Lossin mentions demands that ranged from 900 mg/g/h on day-1 of composting to 325 mg/g/h on day-24 (Lossin, 1970). Regan and Jeris (1970) report 1.0 mg oxygen/g volatile solids/h at a temperature of 30°C and a moisture content of 45%, and 13.6 mg/g at a temperature of 45°C and a moisture content of 56%. A conclusion to be drawn from the results obtained by the preceding researchers is that, not surprisingly, oxygen uptake reflects intensity of microbial activity. Because of the lack of microbial activity, they concluded that it is also indicative of the degree of stability of the waste. If this were to be true, then the oxygen requirement would diminish after the composting mass has passed through the high temperature stage.

Theoretically, the amount of oxygen required is determined by the amount of carbon to be oxidized. However, it would be impossible to arrive at a precise determination of the oxygen requirement on the basis of the carbon content of the waste, since an unknown fraction of the carbon is converted into bacterial cellular matter and another unknown fraction is so refractory in nature that its carbon remains inaccessible to the microbes. The numerical value proposed by Schulze (1960), namely, 510–620 m^3/ton of volatile matter per day is useful with compost reactors equipped for metering air throughput.

The practical conclusion to be drawn from the preceding discussion is that experimentation should be done with the types of waste expected to be composted so as to determine rates of aeration. For windrow systems, the findings would indicate the appropriate frequency of turning. For static piles and mechanized reactors, they would indicate rates of air flow.

Another practical conclusion is that in the absence of unusually strenuous efforts, it is impractical to maintain a completely aerobic state in a composting mass that is larger than about 1 ton. The aim should be to maximize aeration, but to do so within the constraint of financial feasibility. Because financial and, to some extent, technological constraints combine to impose a less than completely aerobic state, in general practice oxygen availability could be a limiting factor.

Conceivably, the compost process could be hastened considerably by enriching the input air stream with pure oxygen. In fact, such an approach has been seriously proposed. Although technically the concept seems to be attractive, it is highly doubtful that the returns would justify the sharply increased cost of doing so.

4.2.4. Moisture Content

Water is essential for all microbial activity and should be present in appropriate amounts throughout the composting cycle. Optimal moisture content in the starting material varies and essentially depends on the physical state and size of the particles and on the composting system used. Normally, a 60% moisture content in the starting material should be satisfactory. Because different materials have different water-holding capacities, an exact generalization cannot be made about optimal starting or time-course moisture levels.

Too little moisture means early dehydration of the mass, which arrests the biological process giving a physically stable but biologically unstable compost.

Excessive water tends to plug pores and impedes gas exchange. However, a proper balance between the needs for available water and gas exchange should be maintained. Excessive moisture in the starting material could favor anaerobic processes, resulting in a slower process and low quality final product.

In modern composting systems, it is possible to add water during the process. In a plant designed and operated for high rates of heat generation, evaporative cooling removes large amounts of water vapor. This dries the material; hence, periodic water addition may be needed to sustain high levels of microbial activity. This will be only possible in conjunction with mechanical turning. Moisture content, however, does not lend itself to continuous or even frequent adjustment, because water addition during the process may affect a multitude of other factors.

At the end of the composting process, the water content should be quite low (about 30%) in order to prevent any further biological activity in the stabilized material.

As stated earlier, permissible moisture content and oxygen availability are closely interrelated. The basis of the close relationship is in the method of carrying out the compost process. All methods involve the processing of the waste, largely in the same state in which it is delivered to the compost site. In that state, it has a moisture content that is about the same as it had at the time it was generated. As such, the oxygen supply to the microbes involved is both the ambient air and the air trapped within the interstices (voids between the particles) of waste. Inasmuch as the rate of diffusion of ambient air into the mass is inadequate, the interstitial air must be the major source of oxygen. Consequently, if the moisture content of the mass is so high as to displace most of the air from the interstices, anaerobic conditions (anaerobiosis) develop within the mass. Therefore, the maximum permissible moisture content is the one above that the amount of air remaining within the interstices is not sufficient to assure an adequate supply of oxygen, i.e., oxygen becomes limiting. The term “permissible” implies a level at which no nuisance will develop and at which the process will proceed satisfactorily.

The maximum permissible moisture content is a function of the structural strength of the particles that make up the material to be composted. It refers to the degree of the resistance of individual particles to compression. The compression refers only to that imposed upon particles by the weight of the mass above them. Obviously, the greater the structural strength, the higher is the permissible moisture content. Examples of such materials are woodchips, straw, hay (dried grass), rice hulls, and corn stover. Permissible moisture contents for mixtures in which such materials predominate are as high as 75–80%. If the particles are structurally weak, they are deformed when subjected to compression, and the collective volume of the interstices is correspondingly reduced. The result is a lessening of the space available for air and water, and the permissible moisture content accordingly is lowered (see Fig. 4.1). Paper is the principal example of such a material. Upon becoming wet, paper collapses and forms mats. Mixtures in which paper is the major material have an upper permissible moisture content of only 55–60%. Finally, as a mass, the material to be composted may have little or no structural strength. For the sake of convenience, such wastes are referred to as being amorphous, i.e., the particles lacking a definite shape. Common examples are fruit wastes, cannery wastes, sludges, and animal manures devoid of bedding material. To compost those materials, it is necessary to add a “bulking” agent. A bulking agent is one that maintains its structural integrity when mixed with amorphous wastes. It may also have the capacity to absorb some moisture. Any material having a high degree of structural strength can serve as a bulking agent. In the absence of a bulking agent, an amorphous material can be subjected to a treatment such

Fig. 4.1. Schematic diagram of particles and space available for air and water.

that it acquires a structural strength that is adequate for composting. For example, upon being dried, chicken manure takes on granular texture. Unless excessively wettened, the granular particles retain their integrity when mixed with fresh manure. In practice, some of the finished compost product is set aside for use as a bulking agent for the incoming waste. An important point to keep in mind when using a dried or composted amorphous material as a bulking agent is that the combined moisture content of it and fresh waste should not exceed 60%.

The critical role of moisture content is not confined to windrow composting; it also applies to mechanized composting, including that in which the material is continuously agitated. As the moisture content of almost any mass is increased (i.e., up to the point at which it becomes a slurry), it takes on a tendency to mat, to clump, or to form balls, or to do all three. By coincidence, the moisture content at which problems begin to be encountered is comparable to the upper permissible moisture contents for windrowed material.

In a discussion on moisture content, the lower levels at which moisture becomes limiting should receive attention. All microbial activity ceases when the moisture content is less than 8–12%. Consequently, moisture becomes increasingly limiting as it approaches that level. In practice, it is good to maintain the moisture content at a level above 40%.

4.3. Course of the Process

To better understand the principles involved and to develop a suitable program for monitoring compost systems, it is important to describe the sequence of events that take place when all conditions are satisfactory. The description begins with the material in place, either in a reactor or in a windrow. Two obvious sequences are the rise and fall of temperature and the sequential change in appearance.

4.3.1. Temperature Rise and Fall

Normally, the temperature of the material begins to rise soon after the establishment of composting conditions, i.e., after the material has been windrowed or has been placed in a reactor unit. The initial rise in temperature is gradual ("lag period"). Immediately thereafter, if conditions are appropriate, the temperature rises almost exponentially with time until it begins to plateau at about 65 or 70°C. Depending upon the system used and the nature of the waste, the period of high temperature (plateau) persists for 1–3 weeks, and then begins to decline gradually until ambient temperature is reached. If conditions are less than satisfactory, the high temperature plateau may last much longer than 3 weeks, although the levels may be lower, e.g., at 54–60°C.

The rise in temperature is due to two factors; namely, heat generated by the microbial population and the insulation against heat loss provided by the composting mass. The latter implies that at less than a critical mass, heat will be lost as rapidly as it is generated and the material will remain at ambient temperature. Under climatic conditions comparable to those encountered in coastal California (Mediterranean climate), the critical volume seems to be in the order of $1\,m^3$. The critical volume is greater in colder climates — especially in regions where strong winds are common.

The heat generated by the microbes results from their respirational activities. Microbes are not completely efficient in converting and utilizing the chemical energy bound in the substrate. Energy not used becomes heat energy. Thus, temperature rise becomes an indicator of microbial activity because the more active the microbial population, the greater is the amount of heat released. The exponential character of the rise in temperature is due to the breakdown of the easily decomposable components of the waste (e.g., sugars, starch, and simple proteins). During this period, the microbial populations increase exponentially in number.

When the readily decomposable material has been composted, and only that which is more refractory remains, bacterial activity diminishes and accordingly the temperature drops. It may be assumed that by the time the temperature has descended to ambient or a few degrees above, the more biologically unstable components in the wastes have been stabilized and therefore the material is sufficiently composted for storage or for utilization.

4.3.2. Aesthetic Changes

If the process is progressing satisfactorily, the composting mass loses the appearance it had as a raw waste and gradually assumes a darker hue. By the time the process is finished, it has become dark gray to brown in color. Change in odor is another eminently perceptible sequence. Within a few days, the odor of the raw waste is replaced by a collection of odors that, depending upon how well the process is advancing, range from a faint cooking odor to one redolent of putrefying flesh. The odors during this stage may be interlaced with the pungent smell of ammonia. If the C/N of the waste is low and the pH of the composting mass is above 7.5, the concentration of ammonia may mask other odors. Eventually, all objectionable and unobjectionable odors either disappear or are replaced by one that is suggestive of freshly turned loam. With respect to texture, the particle size tends to become smaller as a result of decomposition, abrasion, and maceration. Fibers tend to become brittle, and amorphous material becomes somewhat granular.

4.3.3. Molecular (Chemical) Changes

A change not directly perceptible to the senses is the change in molecular structure. The change is manifested by a decline in concentration of organic matter and an increase in stability. (Organic matter often is referred to as "volatile matter" because combustion converts its carbon into carbon dioxide.) Because the compost process is a biological decomposition, oxidation of the carbon in organic solids to carbon dioxide is an important activity. Consequently, a portion of the organic matter is converted to carbon dioxide. The controlled decomposition feature of composting makes it a degradative process in that complex substances are reduced to simpler forms. Complex molecules that are subject to biological decomposition (i.e., are biodegradable) are converted into simpler forms. Molecules that either are only partly or are completely unbiodegradable (i.e., refractory) tend to remain unchanged. The trend then, is toward increased stability inasmuch as a part of the decomposable mass is lost or reduced to simple forms and the refractory materials remain unchanged.

A trend has developed during the past decade to divide the compost process into two stages, namely, the "compost" ("active") stage and the "maturation" ("ripening," "curing") stage. The term "compost stage" applies to the period of rapid rise in temperature and may include the early plateau period. The term "maturation stage" includes the greater part of the plateau period and extends to and beyond the period of temperature decline. The division is strictly arbitrary in that composting takes place throughout the process, i.e., it is not discontinuous.

The division appeals to entrepreneurs for specific systems. With it, they can speak of "composting" as being done in terms of 2- or 3-day detention periods through the use of their particular systems. The accompanying 30- to 90-day maturation requirement is mentioned only in passing. Claims of 1- to 3-day composting are misleading.

4.4. Indicators

A close review of the course of the compost process reveals four particular features that can serve as useful indicators for monitoring the performance of a compost system. They are: (1) temperature rise and fall; (2) change in odor and appearance; (3) change in texture; and (4) destruction of volatile solids (i.e., organic matter).

The magnitude or intensity of the four features is much reduced if the wastes have a heavy concentration of inert material. Tertiary sludge is a good example.

Upon being exposed to the appropriate operating and environmental conditions, failure of the temperature of the feedstock to begin to rise rapidly within 1–3 or 4 days indicates that something is drastically amiss. A highly probable cause is too much or too little moisture. If malodors seem to be developing, then the problem is due to too much moisture. No odor is detected if the material is too dry. Another possible cause is an excessively high C/N. However, even with a high C/N, some increase in temperature should be detected. A pH at an inhibitory level could be a cause. Excessive moisture can be alleviated through the introduction of bulking material or by increasing the rate of aeration. Aeration removes moisture by way of evaporation. Obviously, a moisture shortage is eliminated through the addition of water. The addition of a highly nitrogenous waste (sewage sludge, and poultry, pig, or sheep manure) is the solution for a high C/N. A low pH can be raised through the addition of lime, keeping in mind the guidance recommended in the section on hydrogen ion level.

After the compost process has begun its course, a sharp deviation in any of the parameters mentioned in the preceding paragraphs indicates trouble. Thus, a sudden sharp dip in temperature during the period that normally would be a time of exponential rise is an indication of the existence of some potentially serious problem. In a windrow, the dip generally is due to an excess of moisture. In a mechanical system, it might be malfunctioning of the aeration equipment. If excessive moisture is the cause, increased aeration (turning) is the best remedy for a windrow system. A more gradual but persistent decline during what should be the period of exponential rise or the "plateau" period is a sign either of inadequate aeration or of insufficient moisture.

The occurrence of objectionable odors invariably is a symptom of anaerobiosis caused by an excessively high moisture content or by inadequate aeration. Inasmuch as the causative factor is anaerobiosis, the corrective measure is to increase the supply of oxygen. Consequently, the olfactory sense may be regarded as being an excellent device for monitoring adequacy of aeration. With a mechanized system, the olfactory sense can be supplemented by mechanical devices designed to monitor the oxygen concentration in the incoming and outgoing air streams. Basically, it should be possible to find some oxygen in the outgoing air stream. The presence of oxygen in the air discharged from a composting pile does not by itself imply adequate aeration. Aeration must be accompanied by proper air distribution throughout the pile.

The onset of a persistent decline in temperature, despite the continued presence of optimum conditions (i.e., no factor is limiting), indicates that the process is coming to an end and the composting mass is approaching stability. From past observations, it may be safely assumed that about the time the temperature begins to approach ambient temperature, the composting mass is sufficiently stable for storage and for use.

4.5. Determination of Degree of Stability

As previously indicated, it is not simple to determine the stability and maturity of a sample of compost visually or by means of a single analytical parameter. The attainment of a dark color or an earthy odor is not an indication, because these characteristics may be acquired long before stability is reached. Reaching a C/N lower than 20/1 also is not indicative. For example, the C/N of raw manures may be lower than 20/1. Dryness should not be confused with stability either. It is true that if the moisture content is lower than 15–20%, microbial activity is minimal, and the product may seem to have the external attributes of stability. The actual situation, however, is that as soon as the moisture content of the material is increased, the material assumes the degree of stability it had prior to dehydration. Although the fallacy of equating stability with dehydration may seem obvious, it nevertheless has been seriously offered as evidence by certain entrepreneurs.

Many of the relatively large number of tests that have been proposed have some deficiency that seriously detracts from their utility. A deficiency found in every test is a lack of universality in terms of applicable values. Organic (volatile) solids concentration is an example. Ordinarily, it may be assumed that all substances having a comparable organic solids concentration are equally biologically stable. That assumption is not necessarily valid, because a substance containing organic solids of a refractory nature is more stable than one having an equal concentration of organic solids, but of compounds that are readily broken down.

Some of the early methods proposed for determining stability were the following: final drop in temperature (Golueke and McGauhey, 1953); degree of self-heating capacity (Niese, 1963); amount of decomposable and resistant organic matter in the material (Rolle and Orsanic, 1964); rise in the redox potential (Möller, 1968); oxygen uptake (Schulze, 1964); growth of the fungus *Chaetomium gracilis* (Obrist, 1965); and the starch test (Lossin, 1970).

The final drop in temperature is based on the fact that the drop basically is due to the depletion of readily decomposed (unstable) material. This parameter has the advantage of being universal in its application. The course of the temperature (i.e., shape of the temperature curve) rise and fall remains qualitatively the same regardless of the nature of the material being composted.

Niese's analysis of self-heating capacity is a variation of the parameter, final drop in temperature (Niese, 1963). In the conduct of his method, samples to be tested are inserted in Dewar flasks, which in turn are swathed in several layers of cotton wadding. Loss of heat from the flasks is further lessened by placing them in an incubator. Degree of stability is indicated by rise in temperature. The method has the universality of the parameter final drop in temperature. Its disadvantage is its slowness of completion. It may require several days to reach completion.

Rolle and Orsanic (1964) designed their method to measure the amount of decomposable material in a representative sample. The rationale for their test is that the difference between the concentration of decomposable material in the raw waste and that in the samples to be tested is indicative of the degree of stability of the latter. The basic principle involved in their test is that, essentially, stability is a function of the fraction of oxidizable matter remaining in the composting mass. Hence, degree of stability reflects the size of the oxidizable fraction. The size of the fraction is determined by the amount of oxidizing reagent used in the analysis. Rolle and Orsanic's test consists of treating a sample with potassium dichromate solution in the presence of sulfuric acid. As a result of the treatment, a certain amount of dichromate added in excess is used up in the oxidation of organic matter. The oxidizing agent remaining at the end of the reaction is back-titrated with ferrous ammonium sulfate, and the amount of dichromate used up is determined. The calculation of the amount of decomposable organic matter is as follows:

$$\mathrm{DOM} = (\mathrm{ml})N(1 - T/S)\,1.34$$

in which DOM is decomposable organic matter in weight percent of dry matter, ml is milliliters of $K_2Cr_2O_7$ (potassium dichromate) solution, N is normality of potassium dichromate, T is milliliters of ferrous ammonium sulfate solution for back titration, and S is milliliters of ferrous ammonium sulfate solution for blank test. Quantitatively, resistant organic matter is equal to the difference between the total weight lost in combustion and that degraded in the oxidation reaction.

The basis for Möller's test (Möller, 1968) is the reported incidence of human pathogens and parasites in incompletely composted material, and their supposed absence in the completed product. Theoretically, decomposable materials make possible an intensification of microbial activity and hence an accompanying increase in oxygen uptake, which in turn leads to a drop in the oxidation–reduction potential. Increase in mineralization of the composting material is paralleled by a rise in oxidation–reduction potential. According to Möller, stability has been reached if the oxidation–reduction potential of the core zone of the mass is $<50\,\text{mV}$ lower than that of its outer zone. He provides no method of testing material from a mechanized reactor. No zonation occurs in such a unit. An important obstacle to the use of the oxidation–reduction potential is the lack of accuracy of the test and its vulnerability to a number of interfering factors.

Obrist (1965) relies upon the effect had by degree of substrate stability on rate of growth and production of fruiting bodies of the fungus *C. gracilis*. According to him, growth of the fungus is dependent upon the chemical nature of the waste as a whole. The test consists of culturing the fungus upon a solid nutrient medium into which has been incorporated a pulverized sample of the compost, and allowing the organism to incubate for 12 days at 38°C. At the end of the incubation period, the fruiting bodies are counted. According to Obrist, the more advanced the degree of stabilization, the fewer will be the fruiting bodies. Aside from the disadvantage of the overly long test period, is the serious one of requiring the services of an analyst skilled in mycological techniques.

According to Lossin (1970), the starch test is based upon the assumption that starch is always to be found in a waste, and that the concentration of starch declines with increase in degree of stabilization. Lossin states that three types of carbohydrates occur in wastes, namely, sugars, starch, and cellulose. Not unexpectedly, during the course of composting, sugars are the first to disappear, followed by starch, and finally by cellulose. Lossin reasons that because starch is relatively easy to break down, and all wastes contain starch, no starch should remain if a composted material is to be considered stable. The analysis is based upon the formation of a starch–iodine complex in an acidic extract of the compost material. Care must be exercised in conducting the test because it is easy to arrive at false results. The test again suffers from the inability to set up universally applicable values.

A study was made of the comparative reliability of some of the tests (Wylie, 1957). One of the primary objectives of the study was to find methods by means of which the degree of decomposition of a compost could be quickly and reliably determined. The "transferability" and universality of the methods were to be determined and compared. Findings made in the study showed that of the methods investigated, self-heating, oxygen consumption (4 days), and ratio of oxygen consumption to chemical oxygen demand provided the most reliable results.

Since then, other tests have been developed and are described elsewhere in this publication. Despite the fact that some of these tests were developed several years ago, Niese's analysis of self-heating capacity still continues to be widely used.

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Chapter 5

Systems Used in Composting

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5.1. Introduction

The technology used for composting involves the following three phases: (1) preparation of the feedstock (also known as "pre-processing"), (2) the compost process itself, and (3) the grading and upgrading of the final product (or "post-processing"). The steps involved in the preparation of the feedstock generally include some type of size reduction and segregation of unwanted materials (i.e., contamination). This chapter deals only with the steps associated with the compost and product preparation.

5.2. Purpose of Equipment

One of the key purposes of equipment in composting is to provide the microorganisms responsible for the degradation with an optimum environment within the constraints brought about by financial feasibility. General experience in composting has shown that availability of oxygen is the environmental factor of most concern. Consequently, the design of new equipment for composting has emphasized the development of effective aeration systems (Golueke, 1977; Chiumenti et al., 2005).

5.2.1. Aeration

The source of oxygen for the microorganisms is the layer of air that essentially surrounds each particle. The oxygen that is removed from the air is replaced by CO_2 released by the microbial cells. Eventually, the supply of oxygen in the air surrounding the particle is exhausted, and unless it is replaced by a layer of "fresh" air, anaerobic conditions soon prevail. Consequently, the primary objective in the design of aeration equipment is the renewal of the gaseous environment at a rate such that a sufficient supply of oxygen is always available to the microorganisms. The renewal can be accomplished by: (1) physically moving the particles into a new position and consequently exposing them to supplies of fresh air, or (2) displacing the gaseous envelope while the particles remain stationary (Diaz et al., 1982, 1993).

5.2.1.1. Physical

Physical movement of the particles, also known as "agitation," is accomplished in two ways: tumbling and stirring. During the tumbling process, the particles are lifted and then allowed to drop or fall. The gaseous envelope around the particle is renewed during the mechanical process of agitation. Obviously, the tumbling motion and its aftermath should be accomplished such that the material is not compacted after agitation. Tumbling may be accomplished by "turning" the material. In mechanized composting systems, tumbling is accomplished by one or more means. In some processes, tumbling is brought about by dropping the composting mass from one floor to another or from one conveyor belt to a lower one. In other processes, tumbling is accomplished by introducing the material into a rotating cylinder equipped with interior vanes, in which case tumbling occurs during lifting and falling of the particles in the mixture. In processes involving mechanical stirring, the movement of the mixture of particles is primarily sideways and results in little tumbling action or agitation of the particles.

5.2.1.2. Gas Displacement

In a process in which the particles remain stationary, the layer of air surrounding the particles is constantly diluted or replaced by air forced through the composting mass, hence the term "forced aeration" is applied to such a system. The term "static" frequently is used instead of "forced aeration." The effectiveness of this approach is a function of the even distribution and unobstructed movement of air to all parts of the composting mass.

5.3. Guidelines for System Selection

There are some general guidelines that can be applied to maximize the potential for a composting system to be efficient, produce a product of suitable quality, and be cost effective. The guidelines offered in this section are based on more than three decades of firsthand experience and observation.

The first, and very important, guideline is that a composting system does not have to be technically complicated to be successful. This is based on the fact that efficiency and complexity of the process does not depend upon each other. In fact, excessive complexity in waste processing generally leads to inefficiency.

The second guideline requires that the system to be used be readily adaptable to the labor and economic conditions of the community in which it is to be used. Consequently, an automated composting system would not be the prudent choice for a location in a non-industrialized country that is afflicted by a high unemployment rate and a dearth of foreign exchange. It is highly possible that in that particular situation, a relatively simple, labor-intensive system might be more appropriate than a highly complex one. Under the conditions that are typical in a non-industrialized situation, a complex mechanical composting facility soon breaks down due to the lack of skilled labor, adequate maintenance, and replacement parts. Some of the environmental nuisances that might accompany the use of a low-technology system can be overcome by selecting a suitable site and by enclosing some or all of the composting system.

The third guideline consists of a series of precautionary statements instead of a single guideline, and is particularly applicable to enclosed systems. The first precaution is related to exaggerated claims made by entrepreneurs; such claims should be regarded with skepticism. Claims that a composting system can achieve very high rates of biological degradation or generate zero process residue are likely exaggerated. For example, claims that the entire composting process can be completed in 1 or even 6 days obviously are exaggerated. Even when a highly putrescible waste is processed using a fairly effective aeration system, a minimum of 12–14 days of active composting time is necessary. A careful examination of the claims will show that the claims generally call for a relatively short residence time in the "reactor," immediately followed by an extensive period of retention time in a windrow. The highly unequal division of retention times fits in with the trend to split the composting process into a "compost stage" and a "maturation stage." An examination of the claims for acceleration of the process will show a correlation between the high cost of the reactor and shortness of the claimed compost time. It becomes very clear that the claimed increase in speed is more a function of not discouraging the prospective buyer, rather than of any intrinsic superiority of the reactor. The important point to keep in mind is the total number of days required for the compost and the maturation stages. As will become apparent in the following sections, in most cases the saving in processing time, if any, associated with employing highly complex equipment is not sufficient to offset the additional expenditure that is required.

The best way to evaluate a particular system is to have it observed while in operation by an individual who is thoroughly versed in waste processing and composting.

The same individual should also inspect the compost and its characteristics as soon as it is produced, i.e., the same day. The reason for immediate observation of the product is that samples that are saved for later inspection are not truly representative of daily production because the samples benefit from prolonged storage and from a certain amount of drying. Dryness conceals biological instability and its consequences, e.g., generation of offensive odors. To be able to find hidden weaknesses and potential problems, the observer should be a professional who is completely conversant with composting through firsthand experience. The observation period should take place over a minimum of eight consecutive hours.

Simplicity or complexity of process does not have a major impact on the quality of the product, provided the process is properly conducted. However, the product can be upgraded by further processing.

At this time, attention is called to the remote possibility that a reactor could be designed such that a product could be produced within the retention times claimed even by the more optimistic entrepreneurs. Unfortunately, the capital, operating, and maintenance costs of the resulting setup would be extremely high. An example of such an approach would be to make a very fine slurry of the waste and then subject the slurry to the conventional activated sludge process used in wastewater treatment. Versions of this approach have been applied to the stabilization of wastewater sludges.

In summary, it should always be kept in mind that composting, being a biological process, is constrained by the limitations of a biological system. As was stated earlier, a process proceeds at a rate and to an extent equal only to those permitted by the genetic traits of the microorganisms. No amount of sophistication of equipment can bring about a further increase.

5.4. General Classification of Composting Systems

The large variety of currently available compost systems can be grouped into two broad categories: "windrow" and "in-vessel." The main feature of windrow systems is the accumulation of the substrate into piles. Typically, the piles are between 1.5 and 2.5 m high and usually shaped into more or less elongated windrows. With in-vessel systems, all or part of the composting takes place in a reactor. It should be noted that many of the current in-vessel systems involve the use of windrows for curing and maturation (Dziejowski and Kazanowska, 2002).

5.4.1. Windrow Systems

Windrow systems may be subdivided on the basis of method of aeration into the "turned windrow" and the "forced air windrow." (Synonyms for "forced air windrow" are "static pile" and "stationary windrow.") The windrows may or may not be sheltered from the elements. A classification of windrow systems that no longer is in common use is "open windrow."

5.4.1.1. *Static System*

In the static system, air is either forced upwards through the composting mass or is pulled downwards and through it — hence, the alternative designation of "forced aeration." In both instances, the composting mass is not disturbed.

Despite the fact that the forced aeration system had been proposed and tried as early as in the late 1950s (Wylie, 1957), it was not until the 1970s that it began to receive considerable attention. Even though Senn (1974) successfully applied forced aeration in the composting of dairy cattle manure, the main reason for the resurgence of interest was the apparent utility in the application of the method to the composting of sewage sludge. The system as applied to sewage sludge is the one known as the Beltsville method of composting — so-called after the name of the place of its origin (Epstein et al., 1976). The forced aeration system essentially involves an initial period of drawing air into and through the pile, followed by a period of forcing it upward through the pile. In the pulling or "suction" stage, the air that leaves the system either is discharged directly into the environment, or is forced through a pile of finished compost or other "stable" organic matte (a biofilter). The rationale for the latter procedure is to deodorize the effluent air stream. It has been amply demonstrated that finished compost and other organic materials can serve as an odor filter (Bidlingmaier, 1996; Schlegelmilch et al., 2005). The basic arrangements of an aerated static pile are shown in Figs 5.1 and 5.2.

The system includes the following six steps:

1. mixing of a bulking agent with the waste to be composted,
2. construction of the windrow,
3. composting process,
4. screening of the composted mixture to remove reusable bulking agent,
5. curing, and
6. storage.

The construction of the windrow proceeds as follows: a series of perforated pipes, 10.2–15.2 cm (diameter), is placed on the compost pad. The pipes are oriented

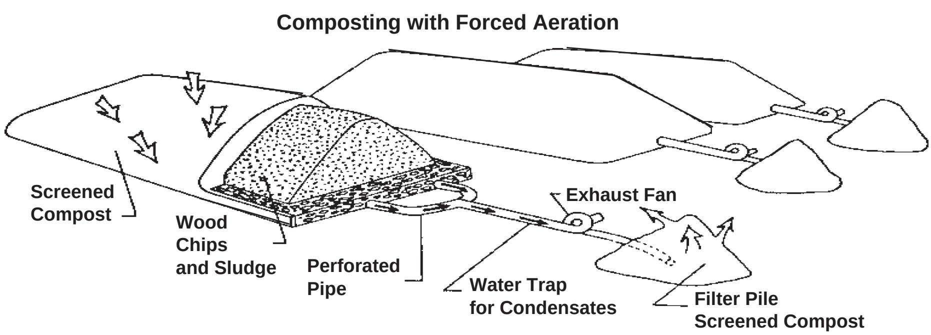

Fig. 5.1. Schematic diagram of aerated static pile composting.

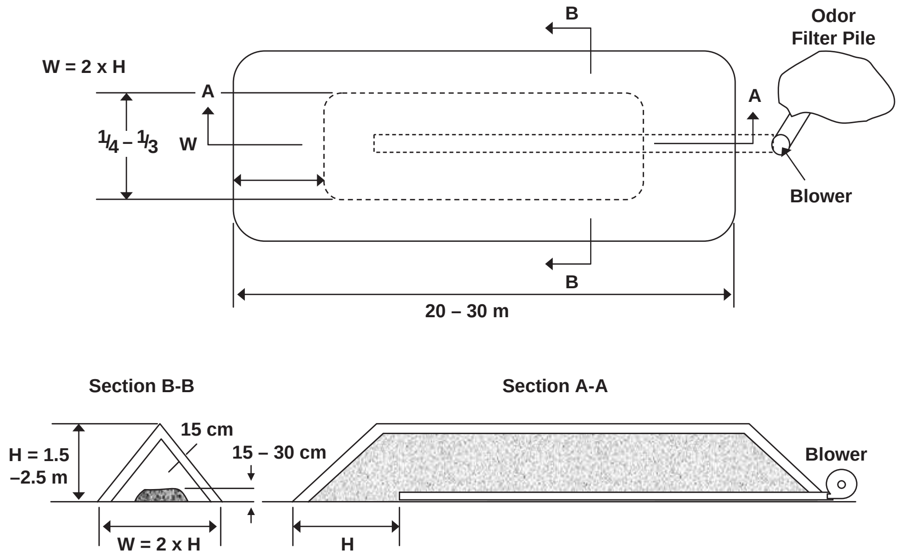

Fig. 5.2. Approximate dimensions for an aerated static pile.

longitudinally and placed parallel to what would be the ridge of the windrow. Short-circuiting of air is avoided by ending the pipes about 1.5–2.7 m from the edges of the windrow. The perforated pipes are connected to a blower through a length of non-perforated pipe. After the network of piping is in place, it is covered with a layer of bulking agent or finished compost that extends over the area to be covered by the windrow of material to be composted. This foundational layer is provided to facilitate the movement and uniform distribution of air during composting. It also absorbs excess moisture and thereby minimizes seepage from the pile. The material to be composted is then stacked on the piping and bed of bulking material to form a windrow, as shown in Fig. 5.1. The finished pile should be about 20–30 m long, about 3–6 m wide, and about 1.5–2.5 m high.

Finally, the entire pile of composting material may be covered with a layer of matured (finished) compost that is about 15 cm thick if the covering compost is screened, and about 20 cm thick if unscreened. The covering serves to absorb objectionable odors from the composting mass and ensures the occurrence of high-temperature levels throughout the composting material. As will be discussed in another section, at the present time there are synthetic materials that can be placed on the windrow to essentially achieve the same results. The arrangement accomplishes a more complete pathogen-kill than would otherwise take place. Experience has shown that a continuous forcing of air through the pile is not necessary to maintain aerobic conditions.

Porosity of the composting mass is a critical factor in forced aeration; as such, it is important that the moisture content be such that the voids be free of water. A safe level of moisture content is one in the range of 40–55%.

Initially, the design of a forced aeration system called for the effluent air to be passed through a small, cone-shaped pile, preferably of matured compost (the mature compost behaved as a biofilter). At Beltsville, these piles usually were about 1.2 m high and about 2.4 m in diameter at the base. The moisture content of the material in the piles should be less than 50%. Since then, the designs of biofilters have evolved substantially. Biofilters have now become integral components of the air management systems in composting operations and other industrial facilities (Haug, 1993; Chiumenti et al., 2005; Schlegelmilch et al., 2005).

In the Beltsville process, the sludge to be composted (approximately 22% solids) is mixed with woodchips (bulking agent) at a volumetric ratio of 1 part sludge to 2 parts woodchips. The compost process requires from 2 to 3 weeks. When the process has reached completion, the pile is torn down and the material is screened. If the bulking material is to be recycled, the screen-opening size should be such that the bulking particles are retained on the screen and compost passes through. Because wet material is difficult to screen, screening should not be performed during rainy days.

A photograph showing the manifolds used to distribute air through the piles is presented in Fig. 5.3.

Extended Aerated Pile

If large amounts of material are to be composted, the so-called "extended aerated" pile can be used. An extended aerated pile has the following arrangement: on day-1, a pile is constructed in the same way as described in the preceding paragraphs, except that only one side and the two ends of the pile are covered with the matured compost layer.

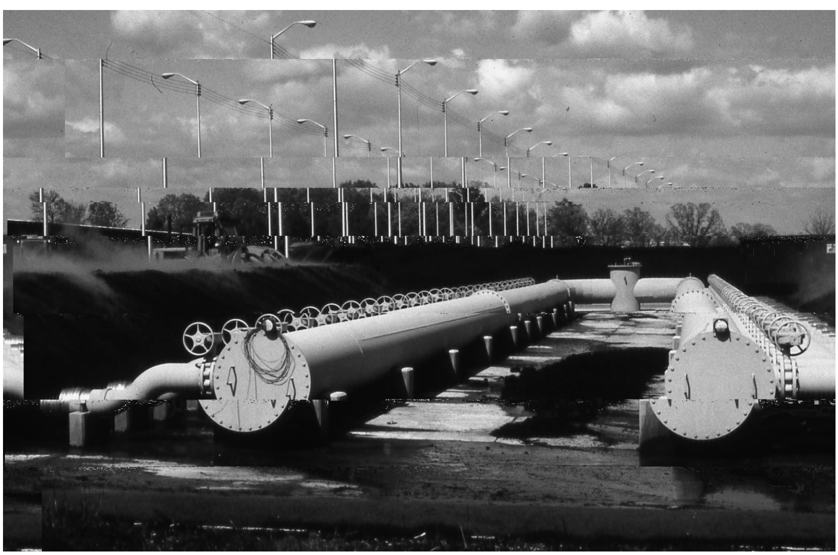

Fig. 5.3. Air distribution system for static piles.

However, the exposed side is lightly covered with matured compost in order to prevent the escape of objectionable odors. On day-2, a second network of piping and bedding is laid directly adjacent to the exposed side of the pile erected on day-1, and the pile is erected in the same manner as was pile-1. This procedure is repeated for 28 days. The first pile is removed after 21 days; the second pile on the day after, and so on. An important advantage of this approach is a substantial reduction in spatial requirements.

The land area requirement for systems that use a single pile is about 1 ha per 7–11 tons (dry weight) of sludge processed. The estimate of about 7 ton/ha allows for sufficient land area to accommodate runoff collection, administration, and general storage.

Economics

The static pile method is perhaps the least expensive method of all of the various types of compost schemes available. This is particularly the case when the quantity of the feedstock is greater than can feasibly be handled by manual labor in a region in which unemployment is chronic, and certainly so when labor is both scarce and expensive. The reasons for the low costs are: (1) limited amount of materials handling required and (2) relatively inexpensive equipment required.

It is difficult to arrive at a generally applicable capital cost for static pile composting because the process and markets for compost are usually site specific. With respect to material and operational costs, the cost for composting a mixture of sludge and woodchips is about $50/ton (2005 US dollars), of which about $10/ton is for woodchips. The cost of woodchips, however, can be much higher in those regions where the woodchips are used for energy generation or other high-value markets.

Limitations

The static pile method is not the most suitable for all types of raw materials and under all conditions. For instance, the method works best and perhaps only with a material that meets the following conditions: relatively uniform particle size, and the particle size does not exceed 3.5–5 cm in any dimension. Granular materials are the most appropriate. A mixture of particles that are too large and that exhibit a wide spectrum of particle sizes can easily result in uneven distribution and movement of air through the pile. Uneven distribution of air through the pile promotes short-circuiting and the development of anaerobic pockets of decomposing material.

5.4.1.2. Turned Windrow System

The turned windrow method is the one that traditionally and conventionally has been associated with composting. The term "turned" applies to the method used for aeration. In essence, turning consists in tearing down a pile and reconstructing it. The details and variations in methods of turning are many. Turning not only promotes aeration, but it also ensures uniformity of decomposition by exposing at one time or another all of the composting material to the particularly active interior zone of a pile. To some extent, turning also serves to further reduce the particle size of some materials. A dubious advantage is the loss of water that is accelerated by the turning process. The loss of water is a definite advantage if the moisture content of the composting material is too high. On the other hand, water loss is a disadvantage if the moisture level is too low. An excellent time to make a necessary addition of water is during the process of turning.

Construction of Piles

The pile should be in the form of a windrow and roughly conical in cross section. However, under special situations, the cross-sectional shape should be adjusted. For example, during dry, windy periods, a pile in the shape of a loaf tending toward a flattened top would be appropriate because the ratio of exposed surface area to volume is lower with such a configuration. Moreover, the volume of the overall hot zone is greater than with a triangular or conical cross section. Conversely, during wet weather the flattened top is a disadvantage because water is absorbed into the composting mass rather than shed. In operations in which the turning is carried out mechanically, the pile configuration that results will obviously be the one imparted by the machine.

Ideally, the windrow should be about 1.5–2.0 m high. In situations in which it is practical to perform the turning manually, the height should be roughly that of the average laborer. At most, it should not be higher than that easily reached with the normal pitch of the equipment used in turning. Another factor that impacts the maximum height is the tendency of stacked material to compact. The height for mechanical turning depends on the design of the turning equipment — generally, it is between 1.5 and 3.0 m.

The breadth of the pile is a function of convenience and expediency. The reason for the latitude is that diffusion of oxygen (natural convection) into a pile makes a relatively small contribution in meeting the oxygen demand of the composting mass. With manual turning, a width of about 2.5 m seems to be suitable. With mechanical turning, the width depends upon the design of the machine — usually, it is from 3.0 to 4.0 m.

In theory, the length of the windrow is indeterminate. For example, the length of a 180-ton windrow (conical shape) of material at a height of 1.8 m and width of 2.5 m would be about 46.0 m. A nearly continuous system can be set up by successively adding each day's input of raw waste to one end of the windrow. In essence, it consists of adding fresh material to one end of the windrow and removing material from the other as it reaches stability.

Arrangement of the Windrows

The specific arrangement of the windrows at a composting facility depends upon two key factors: availability of land and accessibility by the equipment. Whatever the arrangement, the windrows should be positioned such that each day's input can be followed until the material is completely composted.

An important requirement is the space needed to accomplish the turning of a single day's input, whether the turning is done manually or mechanically. With manual turning, the total area requirement is at least two times and more likely 2.5 times that of the original windrow. This is due to the process used for the turning. When the second turning takes place, the windrow is returned to its original position. This double space requirement for each day's increment continues until the material reaches stability.

The area required in mechanical turning varies with type of machine. Some machines accomplish turning in such a manner that as the original windrow is torn down, the new windrow is reconstructed directly behind the machine. This is done either by designing the machine such that it straddles the windrow, or that it has a mechanism for tearing down a windrow and passing the material over the cab to the rear of the machine as it moves forward. The area requirement with such a machine is little more than that of the original windrow, including only enough added space to permit the maneuvering of the machine.

Other types of machines rebuild the windrow adjacent to its original position. The area requirement therefore is comparable to that described for manual turning. A considerable degree of advancement has been made in the design of mechanical turning machines during recent years. Emphasis has been placed on the comfort of the operator, on the size of the windrow, and on the overall space requirements.

Methods of Turning

The equipment that is most convenient to use in manual turning is the pitchfork. Generally, pitchforks have four or five tines. A few things should be remembered when turning a windrow manually. Ideally, in the process of rebuilding the pile, material from the outside layers of the original windrow should be placed in the interior of the rebuilt windrow. Because in practice it is not always convenient to turn the windrow in such a manner, during the compost cycle every particle of the material should be at one time or another in the interior of the pile. If this ideal situation is not practical to attain, as is the case with mechanical turning, the deficiency can be compensated by increasing the frequency of turning. Finally, it is important to keep in mind when constructing the original windrow, and when rebuilding it, not to compact the material.

Frequency of Turning

Essentially, the frequency of turning is dictated by the ratio of available oxygen-to-oxygen requirements. In a practical situation, it is a compromise between need and technical and economic feasibility of meeting that need. Structural strength and moisture content of the material are some of the most important characteristics in determining the frequency of turning. Factors in addition to effectiveness of the turning procedure include pathogen destruction and uniformity of decomposition. A variable factor is the time involved in decomposition desired by the operator. High-rate composting requires very frequent turning because, to a certain extent, rate of degradation is directly proportional to frequency of turning. The drier the material and the firmer the structure of the particles, the less frequent will be the required turning.

When straw, rice hulls, dry grass, dry leaves, woodchips, or sawdust are used as bulking material and the moisture content of the mixture is about 60% or less, turning on the third day after constructing the original pile and every other day thereafter, for a total of about four turnings, is sufficient to accomplish "high rate" composting. After the fourth turning, the frequency can be reduced to once each 4 or 5 days. The same program is applicable if paper is the bulking material, provided that the moisture content does not exceed 50% (Golueke and McGauhey, 1953; Golueke, 1972).

If the composting mass gives off objectionable odors, it means that the mass has become anaerobic, and therefore requires additional turning. In most cases, the onset of anaerobiosis is triggered or is hastened by the presence of excessive moisture. Because it fosters evaporation, increasing the frequency of turning to at least once each day soon results in the disappearance of the odors.

Equipment Used for Turning

A rototiller is quite satisfactory for relatively small operations. Turning by means of a rototiller can be carried out by tearing down the pile and spreading the composting material to form a layer of about 60–120 cm. The rototiller is then passed back and forth through the layer. The procedure should be carried out such that the operator does not walk on the agitated material and thereby compact it. After the material is agitated, it is reconstituted into a new pile. Because of the relatively small capacity of typical rototillers, and the nature of its manipulation, the rototiller is limited to small-scale operations.

Small- and medium-scale operations such as those conducted in some farms can and do use front-end loaders for the turning process. A front-end loader mixing yard waste and biosolids is shown in Fig. 5.4. The operators of the front-end loaders must be properly trained to aerate the mass and at the same time try to place the material in the outer layer in the inside of the pile. Manufacturers of front-end loaders now sell some attachments to the buckets that allow mixing and blending of the materials being processed.

Fig. 5.4. Use of front-end loader for turning piles.

Several types of machines specifically designed to turn compost material are on the market. The machines differ among themselves in degree of effectiveness and durability. The machines can process from a few tons to 3000 tons per hour of fresh compost. Costs (2005 US dollars) of the self-powered machines range from about $200,000 to 300,000.

Site Preparation

During the active stages of composting, the piles should be placed on a hard surface, preferably a paved surface. The main reasons for the paving are: (1) to facilitate materials handling, (2) to control any leachate that may be formed, and (3) to prevent fly larvae from escaping the area. In summary, preservation of sanitation and materials handling are the two key factors. In operations processing less than about 10 tons/day, the paving may consist simply of well-compacted clay as a base with a layer of packed gravel or crushed stone on the surface. In the event that crushed stone and gravel are not available, a layer of soil can be used. The soil should be firmly packed on top of the clay. Of course, when soil is used as the top layer, a problem arises during the rainy season. Paving is especially essential if mechanical turners are utilized. The machines are fairly heavy and, accordingly, can operate properly only on a firm footing. Paving materials in addition to gravel and crushed stone are asphalt and concrete.

Special provisions should be made for collecting the leachate that might be generated. The fresh leachate has an extremely objectionable odor and unless controlled, it can lead to the development of problems. In desert regions, the windrows should be protected from the wind so as to reduce moisture loss through evaporation. In regions of moderate to heavy rainfall, the windrows should be sheltered from the rain. If shelters are not available, the possibility of the windrows taking in an excessive amount of moisture would be particularly high.

Economics

The cost of turned windrow composting depends on a number of parameters, including type and particle size distribution of the organic feedstock(s) (which governs whether or not grinding of the feedstock will be required), level of contamination in the feedstock, local labor rates, permitting requirements, and the use of the compost. If the feedstock is yard waste, then the cost of composting this material using turned windrow technology typically is in the range of $15–30 per input ton inclusive of amortized capital and O&M expenses.

Limitations

The major limitation of turned windrow systems probably is related to public health. The limitations are particularly applicable to operations that involve the processing of human excrement or residues from animals that harbor disease organisms pathogenic to man (zoonoses). The limitation stems from two features of turned windrows: (1) temperatures that are lethal to pathogens do not generally prevail throughout a windrow (in fact, toward the outer layers of a windrow, the temperatures may approach optimum levels for the growth of pathogens); and (2) the turning procedure may play an important role in recontaminating sterilized material with non-sterile material in the outer layers of the windrow in which bactericidal temperatures did not develop. However, repeated turning eventually reduces the pathogen populations to concentrations that are less than infective. This latter condition is reached by the time the material is ready for final processing and use.

Improper or insufficient turning soon leads to a severe limitation in the form of generation of objectionable odors. Even with a suitable protocol, some odors are certain to be generated. However, the latter situation is a characteristic of any system that involves the handling and processing of wastes, whether or not the process is static, turned windrow, or mechanized composting. The period in which odor generation is of nuisance proportions is during the preparatory and active stages of composting, and hence preventive measures need to be taken only during that time. The mere attainment of high temperatures does not imply the absence of objectionable odors.

A relatively slow rate of degradation and the resultant greater space requirement often have been alleged against the use of the turned windrow as contrasted to the "high-speed" composting claimed for mechanical composting. The fallacy of this allegation was discussed earlier, and is only reiterated at this point for the sake of emphasis. While on the subject of rapidity of composting, it should be emphasized that rapid composting becomes a virtue only when high-priced land area and costly reactor usage are involved. If a reactor is not involved and land area is not critical, rapidity loses its advantage. Moreover, under those conditions, the intensity and frequency of turning can be reduced. The reason is that very little odor emanates from a pile of composting material that is not disturbed. It is mainly during the turning process that foul odors, if present, are released from the pile. It should be emphasized, however, that this relaxation in terms of frequency and thoroughness is safe only when no human habitations are nearby, i.e., 150 or more meters away.

5.4.2. In-Vessel Systems

In this section the term "in-vessel" or "reactor" is applied to the unit or set of units in which the "active" stage of composting takes place. Since composting essentially is a biological process, these units are also called bioreactors. In the last few years, the type and number of bioreactors have increased substantially. The growth in new designs has, in part, been due to the regulatory requirements enacted by some European countries and by the EU.

In general, bioreactors can be divided into two main types (Haug, 1993):

vertical and
horizontal.

Horizontal bioreactors can be further subdivided into:

channels;
cells;

containers; and
tunnels.

Another type of reactor is the "inclined" reactor, or rotating drum. Some of the designs of the drums incorporate internal vanes which, combined with the rotating action of the drum, contribute to the size reduction and mixing of the feedstock. This type of reactor normally is used for the active phase of composting and by carefully controlling the oxygen and moisture contents, the composting process can be accelerated.

In-vessel bioreactors can also be classified as a function of the movement of the material. Consequently, the reactors can be denoted as:

static and
dynamic.

The accelerated degradation phase that is carried out in bioreactors generally lasts from 7 to 15 days. The actual detention time depends upon the type of substrate that is used. However, upon completion of the rapid degradation phase, the material that exits the reactor generally is placed in windrows for a curing phase.

A brief description of each type of bioreactor follows.

5.4.2.1. Vertical Reactors

A vertical reactor typically involves some type of cylindrical container or tank. Reactors have been manufactured from steel and concrete and generally are thermally insulated. Reactors have been built ranging in capacities from a few cubic meters to more than 1500 m^3.

In most designs, the material to be composted is introduced through the top and removed from the bottom of the unit as shown in Fig. 5.5. Generally, the material is removed from the reactor through a screw conveyor. As such, the reactors are considered to operate continuously. Photographs showing two vertical reactor systems are presented in Fig. 5.6.

Oxygen is provided to the microorganisms by forced aeration, either through the bottom by means of aeration pipes or through the top by including a manifold from which a series of air lances are inserted into the composting mass. The gas removed from the reactors is transported to a gas treatment system (most of the designs in the late 1980s and early 1990s included a chemical scrubbing system).

Most vertical reactors used for composting solid wastes and municipal sludges have been plagued by a number of operational difficulties and have been closed.

5.4.2.2. Horizontal Reactors

Horizontal reactors are units that, as their classifications suggest, operate in the horizontal position. Horizontal reactors can be further classified into: channels, cells, containers, and tunnels.

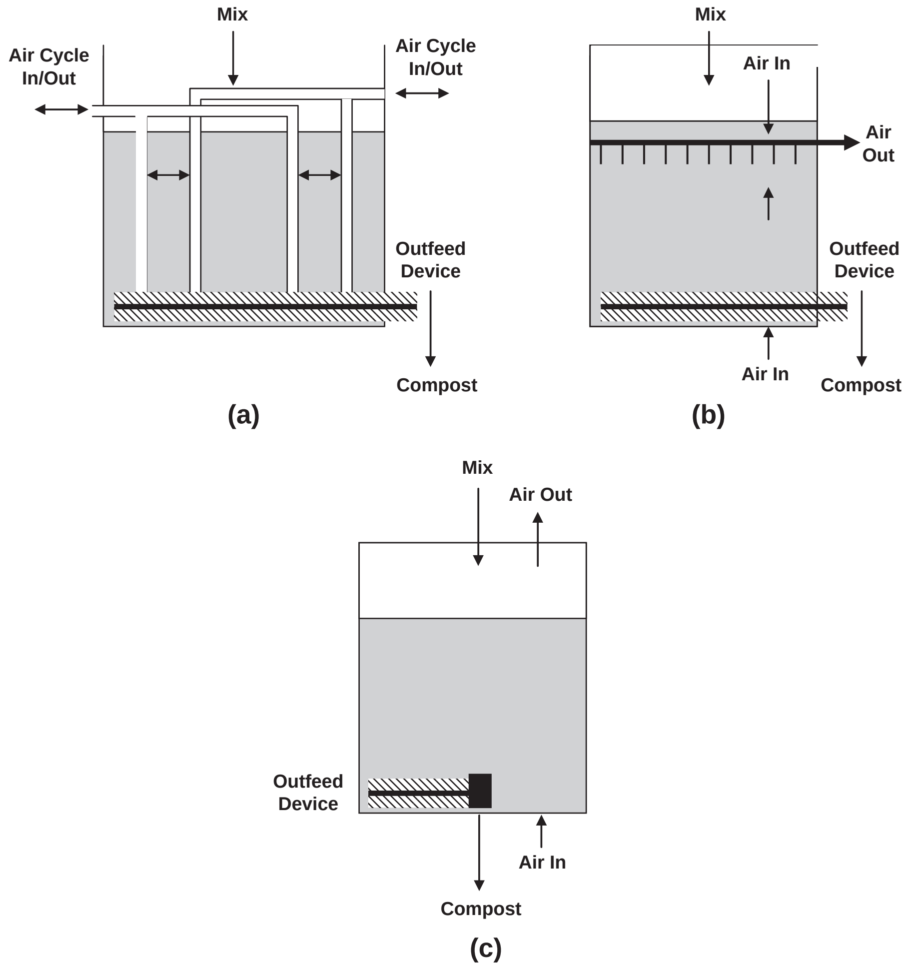

Fig. 5.5. Schematic diagram of vertical plug-flow reactors.

Channels or Trenches

These designs are similar to windrow composting facilities. The main difference between the channels and windrows is that in channel composting, the material to be treated is placed between walls as shown in Fig. 5.7. The walls vary in height from 1 to about 3 m and are placed approximately 6 m apart. The channels generally are 50 m long. In this type of plant, the composting material is kept at aerobic conditions by forcing air through the mass. Typically, forced aeration is carried out in combination with mechanical turning. All trenches are housed inside a building. In most modern designs, to manage the potentially negative impacts of the emissions from the composting mass, the processing building is kept under negative pressure. The air that is removed from the building is directed to

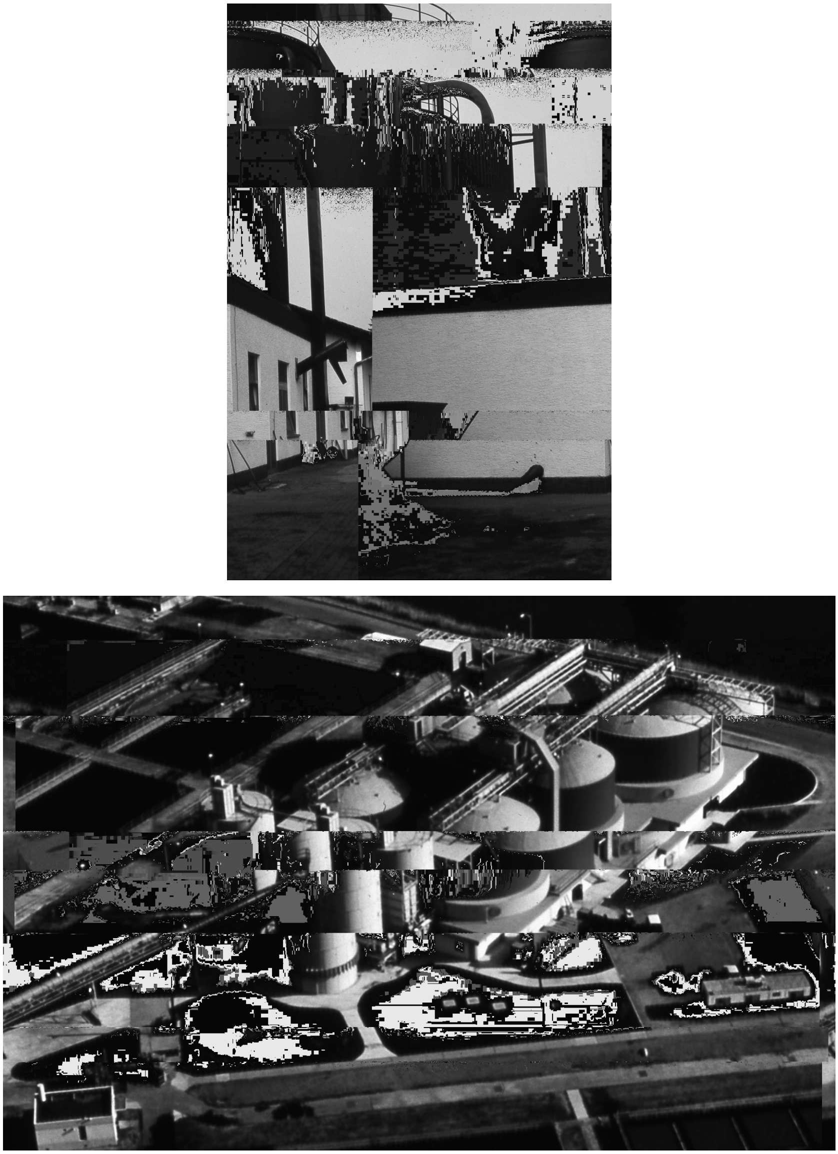

Fig. 5.6. Vertical reactor systems (small-scale, top; large-scale, bottom).

a biofilter or other air pollution control device. Some of these reactors rely on forced aeration, while others use negative pressure. Each one of these options has its advantages and disadvantages.

Generally, the material to be treated is loaded into the trenches by means of a conveyor belt or with automated units that use Archimedean screws. Similar devices are used for

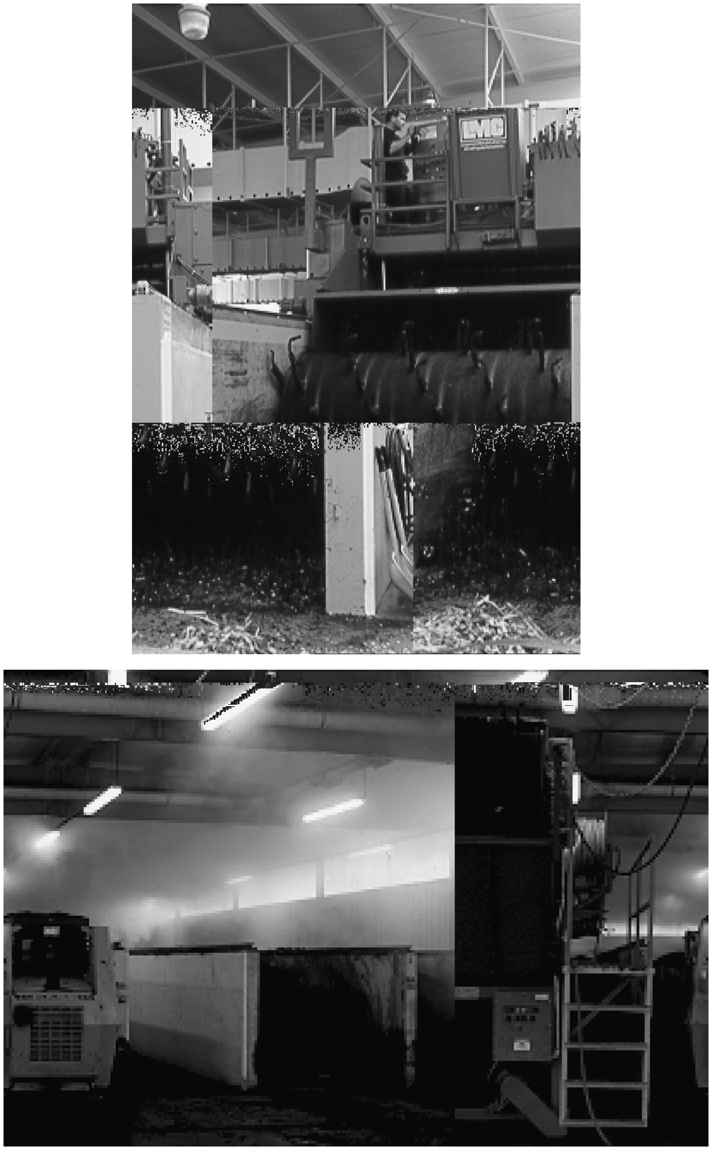

Fig. 5.7. Samples of horizontal reactors (channel).

the unloading process. Front-end loaders can also be used for the loading and unloading process.

These facilities can be operated on a batch basis or a continuous basis. On a batch basis, the incoming material is loaded into the channel as soon as the first phase of the composting process is finished and treated material has been removed. On the other hand, in plants operating continuously, the incoming material is loaded on a daily basis.

The facilities that are operated on a continuous basis can be further classified based upon the direction of movement of the material undergoing treatment. As such, the division is: longitudinal or lateral movement.

Longitudinal Channels In this design, the material to be composted slowly moves from the loading point of the reactor to the unloading portion in a longitudinal direction. The longitudinal motion is imparted by the turning machine; consequently, the rate of movement of the composting mass varies as a function of the design of the turner. However, most machines can move at about 2–3 m per turning. During the intensive phase of decomposition (the first phase of the process), the detention time for the biomass is about 4 weeks. In general, the detention time depends upon the degree of aeration imparted by the turning machine, the availability of a forced aeration system, and the frequency turning.

Longitudinal channels can be subdivided depending upon the shape of the channels. Some of the most common shapes are: straight, elliptical, and U-shaped.

Lateral Movement Channels In this type of design, as the name implies, the composting material is transferred by the turning machine laterally to the next row. Some of the designs include the use of conveyors to carry out the loading operations. Loading is conducted about every 2–3 days, depending upon the volumetric capacity of the channel.

Most of the designs include forced aeration and rely on the use of conveyors to remove the composted material and transport it to the maturation area.

Cells

Cells, also known as biocells, are hermetically enclosed units, generally rectangular in shape, in which the composting takes place. Since the containers are completely enclosed, the environmental conditions of the composting process can be optimized. A number of biocell systems have been developed during the last 10–15 years.

The cells essentially are batch processes and can be built onsite or can be prefabricated. The majority of designs incorporate thermal insulation on all outside surfaces in order to keep heat losses to a minimum.

In a typical operational sequence, the substrate is introduced into the cell by means of front-end loaders or by using a series of conveyors. Once the unit has been filled, the cell is closed and the composting process begins. Typically, the period of intensive composting lasts for approximately 14 days. The actual length of time is a function of the type of material.

Oxygen is provided to the composting mass by means of a forced aeration system. The air is forced upwards through the floor of the cell (using pipes or channels). The exhaust gas is removed at the top of the cell and usually directed to a biofilter or partially recirculated. Some of the most sophisticated designs installed in cold climates incorporate a heat exchanger to pre-heat the air prior to introduction into the composting mass.

Moisture is added to the biomass by means of a watering system at the top of the cell (nozzles and pipes). Any excess moisture is collected and recirculated.

Once the composting process is completed, the material is removed from the cell with a front-end loader.

Some models of biocells include an option to mix the material while in the container. This is accomplished through the use of screw conveyors and moving floors.

Cells are built with a capacity of between 100 and 1000 m^3. Typical measurements are: 6 m wide, 4 m high, and more than 50 m long. The height of the material inside the container must be carefully chosen in order to limit compaction and allow proper air distribution throughout the composting mass.

Containers

Containers usually are rectangular in shape, with volumetric capacities ranging from 20 to 40 m^3. The containers usually are installed in modules. In a typical installation, the top of the container is opened or removed and the feedstock is loaded into the container by means of a conveyor belt or a front-end loader.

Air is forced from the bottom of the container through nozzles. The air that is removed from the container is transported to a biofilter system. Usually, the containers are equipped with a system for water addition. Any excess moisture is removed by gravity through perforations located at the bottom of the container. After about 8–15 days, a door located at one end of the container is opened, the container is tipped (generally by means of a roll-off collection truck), and the material is discharged through opening.

Each module includes between 6 and 8 reactors. A module can process between about 3000 and 5000 tons/year of organic matter.

Tunnels

Tunnels, or biotunnels, essentially are insulated, rectangular boxes made out of metal, concrete, or brick. Typical dimensions of a tunnel are: 4–5 m long, 3–4 m high, and up to 30 m long. The tunnels have specific areas for loading and unloading.

The substrate is introduced at one end of the tunnel on a daily basis. The material is moved toward the opposite end of the tunnel by means of a hydraulic piston (forcing the material forward) or through the reciprocating motion of moving floors.

Moisture and oxygen levels are monitored, and water and air can be added as needed. Air generally is provided by means of compressors and forcing the air through the floor. Some of the designs use centrifugal fans rather than compressors in order to reduce the amount of noise generation. Pipes placed on the roof of the unit remove the discharge air through negative pressure. Some of the units recirculate a certain percentage of the process air. The entire process is controlled by means of a computer. The detention time of the material is approximately 14 days. The overall treatment process lasts about 2 weeks. The aeration systems typically include reversing aeration, and recirculate processed air up to 80%.

Fig. 5.8. View of a typical rotating drum.

5.4.2.3. Inclined Reactor or Rotating Drum

As the name implies, the inclined or rotating drum consists of a rotating cylinder, as depicted in Fig. 5.8. The cylinder is built at a slight inclination so that the substrate to be composted "flows" downward from the top toward the bottom of the unit. The drums are approximately 45 m long and 2–4 m in diameter. The rotational speed is about 0.2–2 rpm. Some of the drums incorporate internal vanes that, combined with the rotating action of the drum, force the material toward the exit and contribute to the size reduction and mixing of the feedstock. The moisture and oxygen concentrations in the reactor are monitored and maintained at optimum or near-optimum levels. This type of reactor normally is used for the active phase of composting and by carefully controlling the oxygen and moisture contents, the composting process can be accelerated.

Under normal operating conditions, the drum is filled to about two-thirds. The detention time for the first phase of composting is about 1 week. However, materials that are readily biodegradable may be processed in 2–3 days. After processing in the rotating drum, the composting material generally is cured for a few weeks in windrows.

5.4.2.4. Economic Limitations

The economics of some mechanized systems are more unfavorable than those of windrow systems. In the early 1970s, capital costs for compost plants in the USA were of the order of $15,000–20,000 per ton of daily capacity. The operational costs were about \$10–15 per ton processed. Present day costs (2005) range from about \$25,000 to about \$80,000 per ton of daily capacity. Upon investigating the costs and the effort involved with a particular mechanized system, it should be borne in mind that a common failing in some of the promotional literature is the tendency to hold down apparent cost through the devices of under-designing the equipment needed and in under-estimating operational requirements.

5.5. Post-Processing

Post-processing involves the various steps taken to refine the finished compost and to meet regulatory and/or market requirements. Post-processing may include one or more of the following unit processes: size reduction, screening, air classification, and de-stoning. In order to achieve adequate separation, the moisture content of the compost should be at or below 30%.

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Chapter 6

Design of Composting Plants

U. de Bertoldi-Schnappinger

6.1. Public Acceptance

The aesthetics of a composting plant must become an important component of the design to achieve sustainable development and to avoid repeating costly mistakes. A proper architectural approach to the design of a composting plant makes a substantial contribution to its integration with its surroundings and better acceptance by the public. The architect can develop a concept for the plant with a regional corporate identity or give form to its uniqueness through an unmistakable architectural design.

Design in the planning process of a composting plant does not simply mean the selection of a colorful final finish for the façades. Of course, such measures can improve previous poor decisions and reduce the monotony of the design; however, with proper planning, the architect should participate in the decision of not only selecting colors and façades but also in the orientation and shape of the various structures that constitute parts of the plant.

In tourist areas, the visitors generally are extremely sensitive to the problems of air, soil, and water pollution, as well as to the visual impact of urban spaces and the landscape.

6.2. Lifespan of Industrial Buildings

In Western Europe, there are many examples of different approaches to building design. Since most of Western Europe has an extremely dense population, loss of open space is considered a loss of nature. Building a structure involves moral and ethical responsibility; buildings in Europe are considered goods with a value of 15 to 30 years for amortization purposes (for example, Germany 15 to 25 years, and Norway 25 to 30 years). In special cases, the lifecycle of buildings can reach more than 100 years.

Examples of European architecture are the Roman aqueducts and bridges, the manufacturing buildings of the Medici, the Fugger, and the Hanse in the Middle Ages. The architect critic Vitruvius said in his *10 Libri di architettura*, "a building has to respect three main principles: construction, beauty and functionality" (Vitruv, 1981). This includes economic aspects as well as environmental sustainability. Every society has the need for buildings that are functional; as much as possible, why not make the buildings good examples of success and not hide them? Quality is one of the main reasons why some buildings are demolished and others are remodeled.

Another approach is to build inexpensive buildings for the composting plants. In this context, inexpensive means to reduce planning costs, to reduce the lifespan of the plant to 7 or 9 years, and to invest the minimum amount of funds and effort on the building and its surroundings. In addition, the equipment costs also are reduced as much as possible. Experience shows that these buildings last for a long time, even when the machinery is old fashioned, changes ownership, or is used for other purposes. The positions of the buildings never change. That means if we, from the first moment, do not develop an appropriate urban concept and building configuration that we anchor this structure, in most of cases, for a very long time. The lack of proper planning results in failures in the performance of the process. The composting plant does not produce high-quality compost, does not meet the legal requirements, and consequently, the compost ends up in the landfill. On the other hand, the basements and walls of the building are "cemented," changes are very difficult or very costly to make, and consequently, the owner and workers of such an inexpensive composting plant live year after year with an unsatisfactory solution.

6.3. Economics of Design

The design and implementation of a composting plant involves a number of contributions from a variety of disciplines such as architecture, civil works, and those involved in the technical facilities. It is important to solve and optimize these contributions during the planning of a composting plant, which helps avoid excessive costs during construction and high maintenance costs for the plant in the future.

An experienced and knowledgeable architect helps influence the following aspects:

- better organization of the processes;
- integration of building and equipment for the composting process;
- less cost for plant management;
- lesser costs during implementation;
- less cost for maintenance of the buildings;
- reduction of emissions;
- reduction of noise, dust, and transport of pathogens inside the facility;
- marketing the image of the plant; and
- fewer costs for future expansions.

Some of the companies that participate in a tender often use schemes or tenders previously prepared for other clients. The result is that the client receives a tender that has not been tailored to his or her own specific needs and requirements. A logical sequence of equipment in the building often is missed. The client needs a consulting team that will select the optimum system for specific needs. The microbiologist analyzes the input material, determines the most adequate bulking agent (if needed), and does the dimensioning according to the retention time and mass loss during the process. Based on the results of analyses by the microbiologist, the engineer verifies the dimensions of each area of the composting process and of the proposed equipment. This control might have feedback to the general local plans and programs. By properly sizing the plant at the beginning of the process and by selecting flexible solutions for expansion, future expenditures are reduced.

With respect to architecture, an adequate cover for the equipment inside, as well as a design of a proper building with adequate access from outside, has to be optimized. The configuration and size of the buildings and the choice of materials for the building are important in relation to its surroundings, but also to the equipment inside the building. The optimum design is a logical sequence of the equipment inside with an enclosure that fulfills the needs of the inside and of the outside. Such a well-planned integration of machinery and building makes an important contribution to keeping the capital costs down during the construction process and to reduce the operation and maintenance costs.

One of the tasks of the architect is to monitor the various functions as they relate to civil works and to architecture. He or she is responsible for demonstrating interferences and conflicts between the architecture and the equipment. Furthermore, the architect must sign and accept responsibility for the proper construction of the buildings, proper integration of the technical facilities, and correct positioning of the spaces, considering future expansion of the plant area. Part of the architecture involves the design of open spaces that should be developed in direct connection with the building and with a similar claim as to quality. The architect develops the design of the open spaces regarding the interconnecting zones and the existing urban or rural patterns.

6.4. Interdisciplinary Teamwork

Cooperation with the local authorities must start even before beginning the design of the project. The integration of agriculture, the agro-industry, as main investors, end users, and producers of biowaste is desirable. There is a common interest necessary to implement the concept, thus helping to reduce the controlling activities to crucial and practically oriented issues. A close relationship among local authorities, the plant construction team, the construction company, and the client is necessary in order to allow non-bureaucratic, fast decisions. Parallel to the planning activities, educating and informing of the public must be attended to.

A well-planned composting plant is the result of interdisciplinary teamwork among several sciences — microbiology; civil engineering; architecture; ventilation, climate, and electrical engineering; geology; and landscaping. This is due to the principle of the division of tasks to avoid failures.

Is the leading role in this team assigned to an architect or to an engineer? History tells us about engineer–architects such as Peter Behrens, Frei Otto, Renzo Piano, and Norman Foster, and architect–engineers like Eugene Viollet-le-Duc, Jörg Schlaich, Ove Arup, and Santiago Calatrava. Professional etiquette is not as important as the characteristics of the person who integrates the professional results of the teamwork.

What is important to a client is that the project manager and the team leader have an equal respect to architecture and engineering. The production of a car that runs, but does

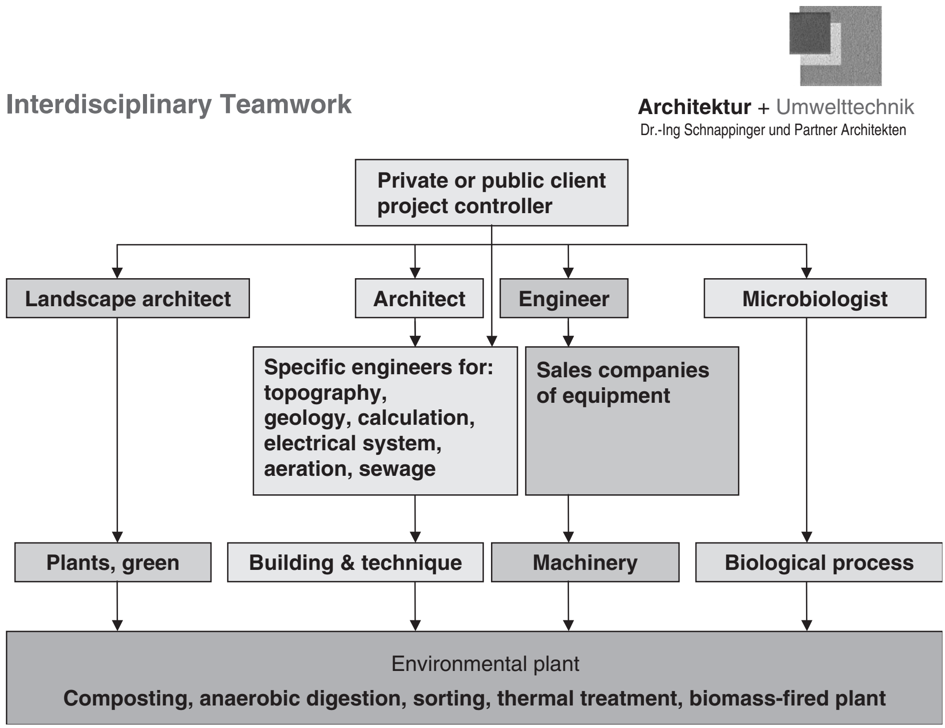


Fig. 6.1. Implementation of environmental plants with teamwork (Source: de Bertoldi-Schnappinger, 2000).

not have a good design is not considered a success. No building, however beautiful the architecture might be, is really beautiful if it does not fulfill its functions.

To avoid disagreement among the members of the planning team, it is important that the client or the project manager clearly define the rights and the duties of each person in the team before the project starts. An example of how an interdisciplinary team could be organized for the design and implementation of an environmental plant is presented in Fig. 6.1.

6.5. Urbanism and Regional Planning

The expansion of our cities into rural regions leads to the destruction of the landscape, and rural areas are transformed into amorphous spaces. The high degree of soil compaction leads to a number of negative effects. European legislation is based on avoiding the growth of industrial zones without any design concept. Industrial zones have to be defined by master plans.

In Europe, the site for a composting plant is evaluated with plans and programs at different levels. A federative organized state regulates the sites by the regional programs and plans of each county. Similarly, a centrally governed state regulates the sites by the programs and plans of the appropriate ministry. The sites are discussed and generally defined within these programs and plans. The site for a composting plant is considered in the regional planning with all of its influences. The solutions have to be coherent with the waste management program of the state. In most European countries, these deliberations lead to a zoning plan and its program, which are valid for the local authorities. The communities finally integrate these areas into their local master plans. This local master plan shows the intended future development of an area.

The implementation of composting plants depends on the economic capacity of the regions: state, counties, and communities. The financial capability of the entity gives the scale for their composting activity, quality of the composting plants, and the collection system. In general, the communities make the final decisions. The communities can collaborate to vote on their activities and finance them. They can establish or contract with a private company. To prepare these strategic decisions for regional and local programs and plans, it is necessary to practice political transparency and to encourage the participation of the citizen (who ultimately is the one who pays for this service) in the very early phases of the planning process.

6.6. Siting

Siting of composting plants normally is a problematic issue, and local authorities have to expect a considerable amount of opposition. A composting plant is considered by the public to be a facility that generates unpleasant odors, attracts additional traffic, and results in additional noise, dust, and congestion. This public attitude toward composting plants has been fueled by a number of bad experiences. One of the primary objectives of this chapter is to help avoid these failures in the future.

Siting the facility must be in accordance with the local political strategy. To define the strategy, the local authorities generally ask waste management professionals to evaluate the quantity and quality of biodegradable waste in a certain region. In addition, an economic analysis is typically carried out in order to find regional markets for the finished compost and to determine their needs. Once these data are collected, it is possible to decide whether or not it is feasible to introduce a centralized or a decentralized concept.

Economic analyses point out that centralized solutions are generally less expensive than decentralized ones. However, the economic point of view is not the only criterion for a decision. In Europe, centralized composting plants have capacities between 35,000 and 50,000 Mg per year; on the other hand, decentralized plants have capacities between 4,000 and 20,000 Mg per year (Bidlingmaier, 2000). Facilities that have capacities of over 50,000 Mg per year are out of scale in any landscape, at least in Europe. In the United States, the size of composting plants varies between 1400 and 10,800 Mg per year (Satkofsky, 2001). In the United States, areas like Texas and Arizona do not have small-scale landscapes such as in Europe. Europeans generally wish to protect the diversity and characteristics of the small-scale landscape.

In Western Europe, there are centralized composting facilities close to big cities, with all of their advantages and disadvantages — especially taking into account that time is needed to establish and build up a market for compost. At the same time, residents and businesses need to be educated repeatedly in order to participate in the programs of biowaste collection and the use of compost. Decentralized concepts with a site close to farms can promote a much better acceptance of compost in agriculture (Jungwirth, 1995). This acceptance is necessary if the concept is to work together with agriculture and agro-industry as the main investors and end users of the compost, and the improvement of the soil in regions with very low soil fertility. There are examples of successful concepts with both decentralized and centralized sites. Decentralized concepts are adapted in rural areas. Centralized composting plants are advisable for application in urban areas with high population densities.

The choice of the site depends on a number of other factors, such as:

- availability and cost of land;
- strategic location;
- infrastructure;
- proximity to other complementary facilities;
- proximity to residential areas;
- geology of the soil;
- distance to groundwater;
- climatic conditions;
- shape of the site; and
- topography.

In general, it is desirable to integrate a composting plant in an industrial area, but this typically is associated with higher costs, since the entire process should be carried out in completely enclosed structures and not outdoors. Storage of the feedstock (the substrate) should be conducted in a building protected on at least three sides against wind, rain, and snow. A site near a farm in a rural area generally requires a cover for the intensive phase of the composting process; however, subsequent phases of the composting processes could be conducted in the open air.

Further, areas from which there is a possibility for germs to be emitted should be completely enclosed: the up- and downloading, the pre-treatment, the process area, and the fine conditioning. Dust and germs collected from the air of these areas should be filtered in a biofilter and/or scrubber, which have to be integrated in the architecture of the plant.

A composting plant for size reduction and stabilization of mixed organic waste should be located as close to the disposal site as possible. This typically is an “interim solution,” because the landfill will eventually be closed. The closure plan for the landfill should aim at making the site inconspicuous in the landscape. The architect should be able to design the building for the treatment facility according to the lifespan of the landfill.

The opposite is necessary for a composting plant for biowaste or for agricultural residues. The intention is to sell a product and to substitute other products in the market. Such a composting plant remains in the society for a long time. For the brand of the product to be perceived as having high quality, the architecture of the buildings has to convey the same message.

6.7. Traffic

Traffic in and out of a composting plant is crucial, as there is a need to maintain collection and transportation costs to a minimum. This leads to the question of whether or not centralized solutions are better than decentralized ones. From an economic point of view, the centralized concept is always cheaper, although the decentralized concept results in less traffic. Access to a commercial or industrial zone is usually accomplished by means of large roads, where the vehicles that collect the biowaste mix with the rest of the traffic. The vehicles used by transporters of goods generally are much larger than the vehicles used for collecting biowaste. Traffic to a composting plant normally is less than that required by the postal service. If there are unpleasant odors or if there is a loss of moisture from the vehicles, these events generally are symptomatic of poor design of the collection vehicles.

Most industrial areas are not connected by railroads. Trucks or container vehicles are primarily used for transporting and selling the products. Sites located on the edge of a town result in less traffic; sites close to a highway close to a town or to other buildings generally are preferable. Sites in the forests or in virgin landscape disturb nature, and it is best to avoid them. Sites in rural areas should be close to farmhouses, to other agricultural buildings, or to greenhouses, and their dimensions should be integrated to the scale of the surroundings.

6.8. Ecological, Climatic, and Regional Aspects

In general, composting plants have the same functions no matter where they are located. However, composting plants in Canada, Norway, Germany, Spain, or Italy have different needs concerning the building and the process. If one considers the four main climatic zones on earth: tropical, dry, moderate, and cold, the analysis of the climatic characteristics has influenced the traditional building configuration and the materials used.

Buildings need less maintenance if they are adapted to their environment and "live" in harmony with the regional climatic conditions. The architect has to consider the specific regional, cultural, and climatic conditions to plan the building. The architect has to consider the shade and solar-heating on a building, as well as wind and vegetation. Furthermore, the architect has to consider the relative humidity and the amount of rainfall at the site. In hot zones, one has to take into account the high evaporation rates, the need for shade for architectural elements or for plants, shelter against wind with fences, and cooling with wind or solar cooling inside the administration building. In a dry zone, where there is a low air-humidity, one can use evaporative cooling (Daniels, 1995).

In cold zones, one has to consider that there is reduced microbiological activity at temperatures below 0°C, and the buildings have to be insulated. The building design also has to consider the load of the snow that accumulates on the roof.

6.9. Accessibility

Access to a composting plant should take into consideration the fact that collection vehicles do not arrive at a steady rate, but have peak periods. A queuing area, which is not public space, must be incorporated into the design next to the entrance to the facility and to the weigh bridges (scales). Concerning the size of the plant, the queuing area should have a length of three to five times the size of the collection vehicles. Furthermore, the entrance should be divided such that access for private vehicles (with parking) is permitted without disturbing the activities on the scales.

The logistics of the roads and turning spaces for the delivery vehicles have to be carefully designed. It is not necessary to surround the entire building with asphalt so that the visitor gets the impression of a "highway" around the building, as shown in Fig. 6.2.

It is better to find a reasonable hierarchy according to the frequency of use. The architect has to locate the approach and exit roads and the turning spaces for the vehicles. The size of the courtyard of the composting plant must respect the turning radius of the largest vehicles. The architect also has to include access for passenger cars, and the routing of visitors and clients to the composting premises. Parking areas for visitors, clients, and workers have to be integrated in the open-air space concept. The architect has to develop concepts for providing shade for the parking areas.

The flooring of areas of the plant that are not used to place compost and/or other material that might produce leachate should not be built with a permeable material. However, areas with heavy traffic or areas for the storage of finished compost have to be built of asphalt–concrete or concrete. The architect must turn all of this diversity into a functional, cost-effective, and aesthetically pleasing design concept.

Fig. 6.2. Poor example of accessibility and parking concepts.

6.10. Building Configuration

The configuration of all the units of a composting plant has to be not only as required by the necessity of the machinery, but also by the need of existing urban patterns and an aesthetical solution for the building. Clients often wish to conduct an open tender in order to determine the least expensive and the best technical solution for the composting process. The client receives many technical configurations for the process, but no solution for the architectural problems. The conditions of the ground, site, size, and shape of the building and the roof are all factors that determine the best and most economical solution for the facility. The architect should participate in the very early phases of plant design. He starts his work by finding a building configuration for the different operations after the engineer and the microbiologist have finished the dimensioning of the spaces necessary for the processes.

What the architect means by design of building configuration is described by two projects for composting plants in Germany (de Bertoldi-Schnappinger, 1994). The first project is the composting plant in Haßloch, a small city near Mannheim-Ludwigshafen, in Rheinland-Pfalz, Germany, as shown in Fig. 6.3. The input to the plant is 35,000 Mg of biowaste per year. A small recycling area is planned for private households. The site is located between a main road and a railway line in a small-scale, agricultural landscape. Fig. 6.4 shows the engineering concept at the beginning of the project.

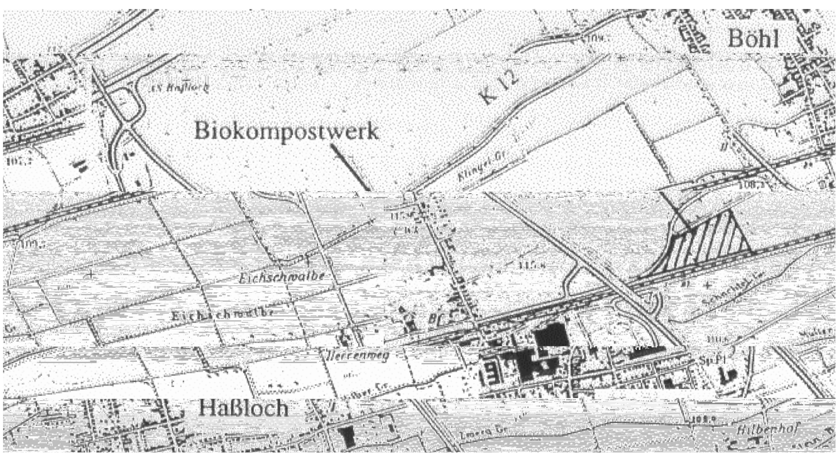
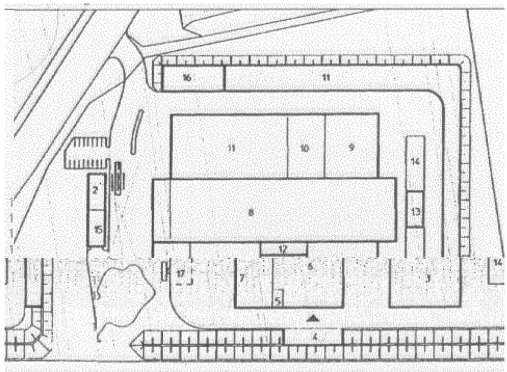


Fig. 6.3. Map of the site for a composting plant.

Project:	Bio Waste Composting Plant in Haßloch-Ludwigshafen, Germany
Client:	GML Gemeinnützige Müllheizkraftwerk GmbH, Ludwigshafen
Technical Facilities:	Planning Team Goepfert, Reimer & Partner, Hamburg and Prof. Scheffold & Partner, Düsseldorf
Architecture:	Ulrike de Bertoldi-Schnappinger, Architektur + Umwelttechnik, München-Pisa



1. Scales
2. Administration building
3. Bulking material
4. Bulking material storage
5. Electrical equipment
6. Flat bunker
7. Pretreatment area
8. Composting area
9. Fine conditioning
10. Container station
11. Finished compost storage
12. Blowers
13. Blowers and scrubber
14. Biofilter
15. Maintenance shop
16. Recycling area
17. Fuel and washing area

Fig. 6.4. Composting plant at Haßloch, Germany (engineer's concept before starting collaboration with the architect).

The areas for the various operations (described with numbers) are calculated with respect to the input of the plant and positioned relative to the flow of the material. The plant is surrounded by a 4-m-high earthen wall, where the soil removed for the buildings is stored. Furthermore, the earthen wall is used for noise suppression. The different surfaces or "squares" depicted in Fig. 6.4 have different flat roofs with different heights. The flat bunker (6) and the storage area for the bulking material (3) are separated by a small courtyard. The pre-treatment area (7) finishes parallel to the composting area (8).

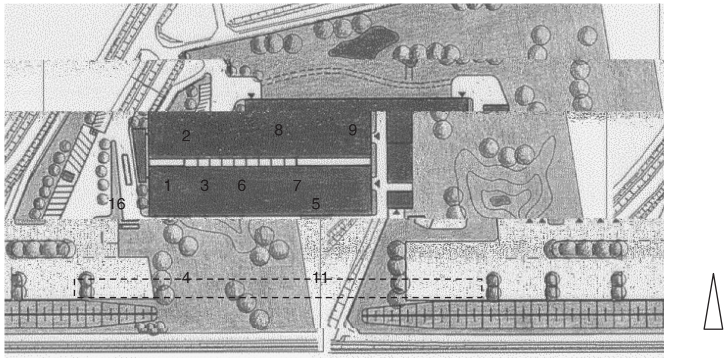
The management building (2) is far from the loading area (6) and from the pre-treatment area (7), where constant control would be necessary. The biofilter (14) is surrounded by access roads on three sides, although it is large enough so that the material of the biofilter needs to be changed just once a year.

The conceptual plan does not show integration between plants and green spaces. The buildings essentially are "floating" on a lake of asphalt. The access road to the plant surrounds the entire building. The access road for the fire department (brigade) is, in case of a fire, much too close to the buildings. The water supply for the fire brigade is stored in a prefabricated concrete tank. The entrance to the parking places is directly in front of the scales and the traffic to the recycling area has to cross the main access road.

The drawing in Fig. 6.5 shows the final building configuration of the plant as a result of the teamwork with the architect.

As the figure shows, the building configuration has been reduced to one main building with two inclined roofs and a light shed. The roof is metallic. Water from the roof is collected only on the north and south façades of the building.

On the north side, the water is drained directly into the ground, and the vegetation is allowed to grow close to the façade. These decisions reduce maintenance costs. The design



1. Scales
2. Administration building
3. Bulking material
4. Bulking material storage
5. Electrical equipment
6. Flat bunker
7. Pretreatment area
8. Composting area
9. Fine conditioning
11. Storage area for compost
16. Recycling area

Fig. 6.5. Composting plant at Haßloch, Germany (final solution after collaboration with the architect).

Project:	Bio Waste Composting Plant in Hassloch-Ludwigshafen, Germany
Client:	GML Gemeinnützige Müllheizkraftwerk GmbH, Ludwigshafen
Technical Facilities:	Planning Team Goepfert, Reimer & Partner, Hamburg and Prof. Scheffold & Partner, Düsseldorf
Architecture:	Ulrike de Bertoldi, Architektur + Umwelttechnik, München-Pisa

of the plant includes a main courtyard in between the railway track and the south façade.

The entrances to the main building are from the north side; the two entrances to the composting area in the north are to be used only for maintenance. The storage area for compost (11) is now located on the south end of the courtyard along the sound wall. The storage area might be covered with a roof or may be left (as is shown in the drawing) without a roof. The excavated soil has been stored along the railway tracks for noise reduction.

The different traffic spaces are arranged with a hierarchy. The road for the fire brigade is green and to be used only in case of an emergency. The water for the fire brigade is now stored in a pond. The number of roads and the amount of space inside the plant has been reduced to a necessary minimum. However, the turning areas for the trucks have become more comfortable than in the original design. The total amount of covered ground has been reduced.

The administration building (2) is situated symmetrically to the main building, as it is the scrubber/biofilter. The shape of the administration building takes into consideration the path of the sun.

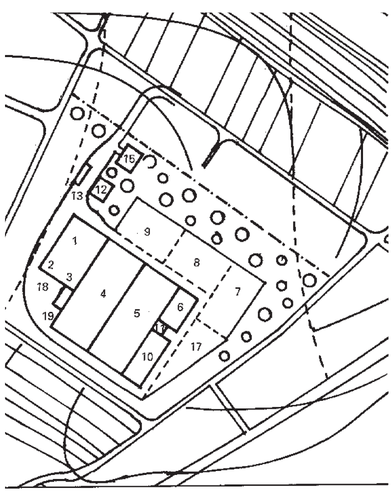
The architect found a solution for the building configuration that positively integrates the composting building into its environment. The view from a traveler passing by the area on the train is led from a little hill to the roof with the light shed. The car driver on the road would look at the north façade of the plant and the pond surrounded by plants and flourishing vegetation.

A three-dimensional model of the plant elements helps determine the best building configuration for each individual situation. Clients should not hesitate to invest in models or in three-dimensional computer animation.

The following example (Fig. 6.6) of a composting plant in Esslingen, Germany (capacity of 50,000 Mg per year), is shown as in the previous paragraphs in the two different phases of work: the first technical proposal and the final result of the teamwork.

This composting plant is located on a hill in a protected regional park. The hill is inclined to the southeast in the direction of the freeway that links Munich with Stuttgart, Germany. The building configuration of the first engineering concept shows a compact, nearly cubical building (4, 5) with some blocks (1, 2, 3, 6, 10, 13) on a slightly inclined plateau. The excavated soil forms an earthen wall around the buildings. A courtyard has not been included in the design. The access road surrounds the building complex. The model photo of the first engineering concept (Fig. 6.7) shows a slight variation of the solution presented before with an entrance located on the opposite side.

The central idea for the final building configuration is the embedding of the buildings into the landscape, forming a courtyard. As shown in Fig. 6.8, the main building (1) is



1. Flat bunker
2. Bulking material
3. Pretreatment area
4. Intensive composting area
5. Post composting area
6. Fine conditioning
7. Compost storage
8. Finished product storage
9. Finished product storage
10. Biofilter
11. Blower
12. Administration building
13. Scales
15. Maintenance shop
17. Biological water treatment
18. Washing area
19. Fuel station

Fig. 6.6. Engineer's concept before starting the collaboration with the architect.

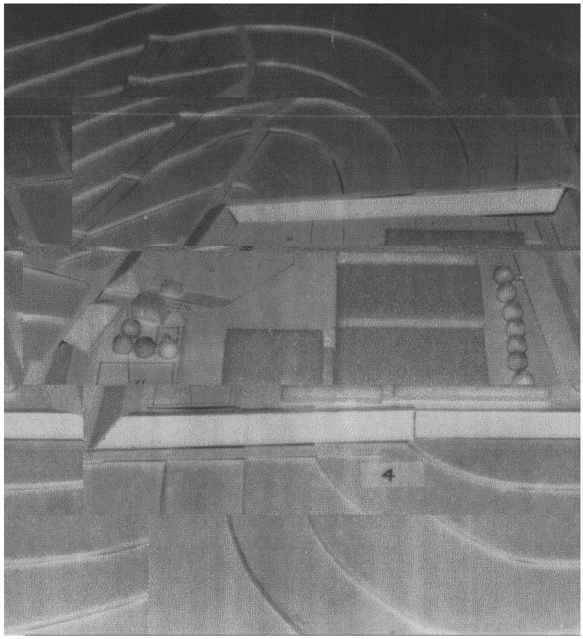
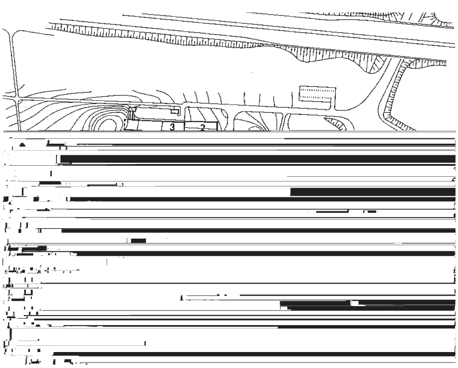


Fig. 6.7. Poor example of integration into the landscape.



1. Building for composting process
2. Administration building
3. Maintenance shop
4. Pond
5. Compost storage; finished products
6. Biofilter

Fig. 6.8. Composting plant at Esslingen, Germany (final result of the teamwork with the architect).

Project: Client: Landkreis Esslingen; Technical Facilities/Project Management: Fichtner Ingenieure, Stuttgart, Germany; Architecture: Ulrike de Bertoldi, Munich-Pisa

inserted into the existing hill and has an extensive green roof. The compost storage (5) is located on the opposite side with the south façade inserted in the ground, so that the plant is visible from the road leading to the castle Burg Teck, a well-known tourist attraction, with a green façade and a pond. The accesses to the building are concentrated in the courtyard.

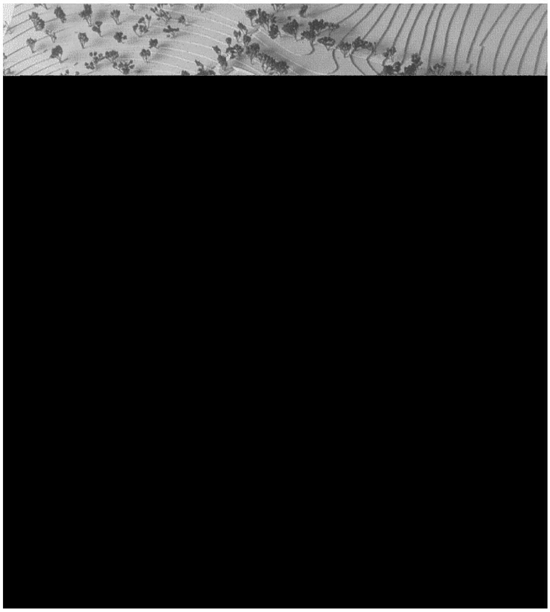


Fig. 6.9. Top view of the model of the composting plant at Esslingen, Germany.

The administration building closes the courtyard to the southeast in the direction of the highway Munich-Stuttgart and shows the composting plant to the passing drivers with the façade of an attractive office building that looks like a new company producing and selling consumer products. A top view of the model of the facility is presented in Fig. 6.9.

6.11. Design of Open-Air Space

Landscape architects specialize in the design of open-air spaces regarding the architecture and selection of the correct type of plants. In most of the states in Western Europe, it is mandatory to include a landscape architect in the design of the facilities. His work is a part of the permit planning. He or she chooses the plants and vegetation for the extensive green roof. The building and facility architect assumes responsibility for the technical construction and the strength of the green roof. Experience shows that companies that produce soil amendments and soil for gardening do not generally have an understanding of the integration of plants and green spaces. It is, therefore, highly recommended to incorporate the landscape architect or at least a landscaper in the initial planning phases, because green walls and roofs compensate for the loss of ground and have a positive influence on the microclimate.

The architect and the landscape architect work very closely together, because landscaping does not imply hiding façades that are not well designed behind plants, but developing

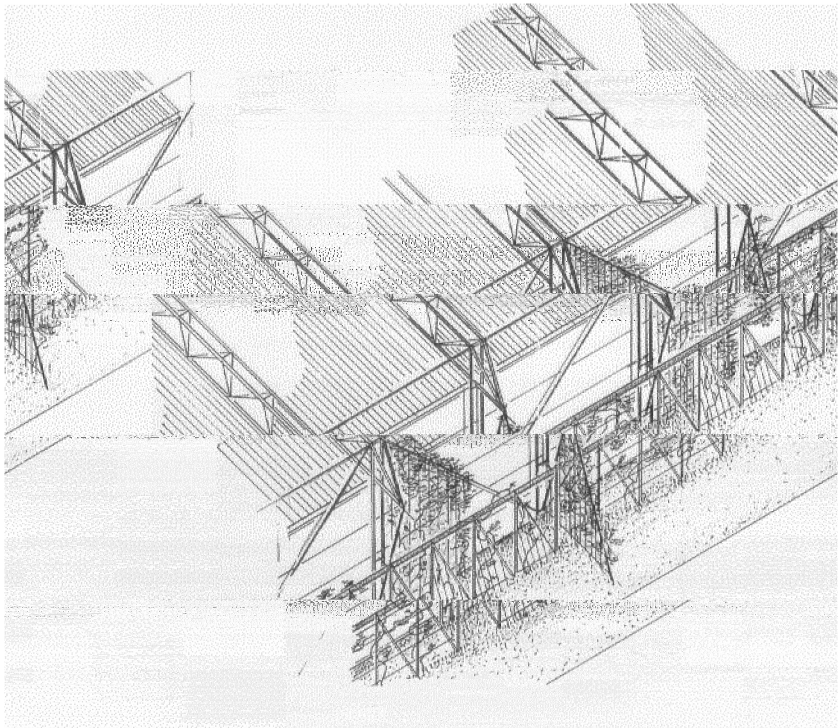


Fig. 6.10. Sample of construction design that integrates plants (architect: Ulrike de Bertoldi).

coherent plant architecture. Vegetation should provide shade during summer and allow the sun in during winter. In hot areas, plants are the source of natural cooling. Parking spaces without the benefit of plants are an unsatisfactory solution. The open-air facilities form a transition zone between the building and its surroundings. It should focus on a homogeneous networking with the existing trees, plants, and greenery. An example of how construction design can be integrated with plants is given in Fig. 6.10.

6.12. Construction and Corrosion

The choice of suitable materials and construction elements, as well as a three-dimensional model of the construction elements, are important factors for successful architecture. The material used for the buildings has to be sustainable. This means that its production has to be conducted with less energy and with minimal environmental damage; in case of replacement, the material used for construction has to be easily recyclable. Building materials produced in the neighborhood can be the basis for the development of the architectural concept for the plant.

The main principles for the design of the construction include:

- force and energy transmission;
- safety and reliability;
- aesthetics;
- strength;
- thermal expansion;
- design to limit wear;
- ergonomics and user safety;
- design for ease of manufacturing and inspection;
- design for ease of assembly;
- operability and maintainability;
- design for ease of recycling;
- possibility of transport;
- cost; and
- time for construction.

The high humidity and temperature of the air must be given proper consideration in enclosed composting systems. The temperature inside the composting system generally is higher than the temperature of the surroundings. Therefore, the moisture in the air condenses on all surfaces, and the condensate contains aggressive acids and ammonia. The pH of the condensate changes during the process from around 5.5 to 8.5.

The usual measures against corrosion are not effective for the process area of a composting plant. Normal protection against corrosion in steel is fire coating with zinc or stainless steel; however, neither method is resistant against the condensate. Table 6.1 shows the

Table 6.1. Materials for construction regarding their resistance to corrosion

Material for the main construction	Resistance against condensate (intensive composting area)	Fire resistance (minutes)	Risks
Wood	No	30/60	Fungi growth
Plywood	Good	30	Change of fittings
Wood with aluminum coating	No	30/60/90	Change of fittings
Steel	No	0	Slow corrosion
Steel fire coated with zinc	No	0	Slow corrosion
Stainless steel	No	0	Slow corrosion
Aluminum	No	0	Slow corrosion
Steel with alloy	No	0	Slow corrosion
Steel with duplex coating	Good	0	Change of fittings
Concrete	No	30/60	Corrosion in cracks or creep
Concrete with protection	Good	30/60	
Concrete waterproof	Good	30/60	Corrosion in cracks or creep

advantages and disadvantages that should be considered when choosing construction materials for the buildings.

In general, it is not recommended to design the wing assembly for the process area of the composting plant inside the building. It is better to put the wing assembly outside of the building. Any construction inside the building has to be designed so that it is as least divided as possible, accessible, and offering the condensate no possibility to collect on the material, forming pockets of water or dirt.

The condensate not only runs down the walls of the main construction, but also along the equipment, and almost everything is touched by this medium. The grid of the joints has to be carefully planned, considering the necessary inclinations to drain the surface to certain points or lines. The liquid should be collected and led to the collection basin. A listing of construction materials used for walls indicating their resistance to corrosion is provided in Table 6.2.

Table 6.2. Materials for walls regarding their resistance to corrosion

Material of walls	Resistance	Fire resistance (minutes)	Risks
Concrete	No	30/60/90	Corrosion in cracks or creep
Concrete with protection	Yes	30/60/90	Corrosion in cracks or creep
Glass	Yes	30/60	
Plywood	Yes	30	Corrosion in cracks or creep
Wood	No	30/60	Fungi
Steel panels	No	0	Slow corrosion
Steel panels with protection	Yes	0	Change of fitting
Aluminum panels	No	0	Slow corrosion
Epoxied resin fibers panels	Yes	0	
Plastic panels	Yes	0	

Materials such as concrete or steel should be coated with protective paint. It is important to consider the following guidelines:

- avoidance of mixing of different products;
- thickness and number of layers;
- application methods (airless spraying, coating, rolling, painting);
- design of construction;
- accessibility of construction;
- lifetime of the building;
- planning of place, time, and duration for the painting to take place; and
- protection against inclement weather.

The protection normally does not need to be renewed, but requires careful maintenance. The architect can facilitate the maintenance by incorporating working stairs and working footbridges into the design. Sometimes, the stairs for fire protection can also be used for corrosion maintenance.

Information about the thickness of the protective medium and the impact of the number of layers in maintenance is given in Tables 6.3 and 6.4, respectively.

Table 6.3. Thickness of layer and drying time for protective medium

Protective medium	Thickness of layer (in μm)	Drying time (approx. hours)
Chlorinated Indian rubber	40	8
Epoxy resin	80	16
Polyurethane	80	16
Duplex system	Fire coating + painting	

Table 6.4. Number of layers of the protective medium and the approximate influence of the maintenance time

Basic layer (number)	Cover layer (number)	Depth of layer (μm)	Approx. frequency of maintenance (time)
1	—	40	3 months
2	—	80	10 months
2	2	160	12–15 years
2	2	240–320	15–25 years

6.13. Flooring

6.13.1. Delivery Area

The flat or deep bunker is built in concrete with a highly protected surface against mechanical damage. The floor has to be planned with high and low points in order to allow the possibility of cleaning the bunker using dry methods or by using water. The point for collecting the wastewater must be placed at a location away from the storage area for the waste.

6.13.2. Processing Building

The floor of the processing area generally is filled with pipes for the aeration system. The floor for the processing area is built with prefabricated concrete plates that cover the piping system. These plates have perforations to allow airflow.

The floor of a processing building, which is not accessible, has a drainage and ventilation system covered with a permeable sheet and with wood chips. A view of the floor of a composting building is provided in Fig. 6.11.

As the walls of the building might be wet due to condensation, the architect has to carefully plan for the drainage of the liquid. Materials commonly used for building the floor of the intensive composting area are listed in Table 6.5.

Fig. 6.11. Floor of a composting building, Heidenheimer Platte (Bidlingmeier, 2000).

Table 6.5. Material for the floor of the area of intensive composting

Material for the floor	Resistance against condensate	Risks
Concrete waterproofed	Good	Corrosion in cracks or creep
Concrete with protection	Good	Corrosion in cracks or creep
Concrete waterproofed with helicopter finish	Good	Corrosion in cracks or creep
Asphalt	Good	Permeable to condensate
Prefabricated concrete plates or stones (z.B. Bikovent Steine ELWU Steine, Rottair System)	Good	

6.13.3. Composting Tunnels

Composting tunnels are offered in prefabricated steel construction, prefabricated concrete, or in concrete built onsite. In the case of the prefabricated steel tunnels, the service life and wear is considered less important, as the container can be repaired or completely changed at the end of its lifecycle. The floor is built with perforated steel panels.

In the case of concrete tunnels, the construction has to be waterproof and precise. The reinforcement has to be covered with more than 3 cm of concrete. The floor might be treated with a helicopter finishing, adjusting the tolerances of the concrete, and allowing for the construction of a perfectly horizontal floor. The entrance to the tunnel must consider

Fig. 6.12. Sample of a tunnel with spicket floor (WTT, 2000).

the construction of a seal from the concrete walls to the steel door. An example of a tunnel using a spicket floor is provided in Fig. 6.12.

6.14. Protection for the Construction Parts

In areas where it is possible that a vehicle may crash into columns or walls of the structure, the architect has to design a mechanism for protection. For example, in the delivery area, which might be combined with the pretreatment area, it is necessary to protect the columns, the equipment, and the walls, which might separate the different materials in the bunker. The walls or columns in the loading zone in a deep bunker normally have to be protected. The architect can design metal or concrete constructions, which should be painted with red and white or yellow and black stripes, or might get a red light on the top to be visible in the dark. A photograph showing protection for the entrance gates is provided in Fig. 6.13.

6.15. The Roof

For extremely flat buildings with large dimensions, such as those for composting plants, it is very useful to find architectural solutions that are not monotonous. The ventilation system for the building or the local landscape can be the reason for its shape. The shape of the roof should be designed according to the general concept and the building configuration of the plant. The roof might take the form of waves or be slightly inclined or flat. It might

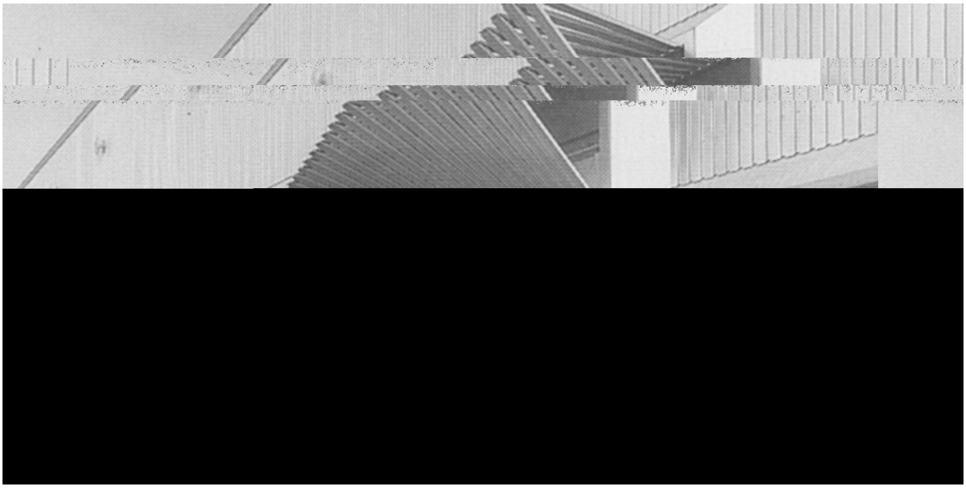


Fig. 6.13. Sample of the protection for the entrance gates.

be designed in metal or covered with a "compost-composition" for dry climates, so-called "extensive green roof." An example of a composting plant using an extensive green roof is shown in Fig. 6.14.

In general, there are industrial roofs that include two layers of steel panels, which are insulated from 5 to 12 cm, depending on the climatic conditions. Another solution is to use a metal panel as the first layer, to put in insulation, and cover the roof with a plastic sheet. The plastic sheet can be protected with an extensive green roof. The use of a green roof has the following advantages:

- protection of the plastic cover against UV-rays;
- insulation of the roof; and
- collection of dust, retention of water, and lower water flow rate.

Fig. 6.14. Composting plant, Esslingen, Germany (architect: Ulrike de Bertoldi Munich-Pisa) (Note: Composting plant with an extensive green roof).

The roof construction with extensive green negates the need to construct a second metal layer, making this solution inexpensive. The choice of material for the roof should consider the production of condensate in the area of intensive composting, where the first layer should be plastic sheeted or plastic coated, because steel or aluminum panels are not resistant against the condensate.

6.16. The Façades

The façades of a composting facility are defined by the gates for the trucks and the amount of lighting needed in the different areas of the plant. However, it is not necessary to plan a façade for a composting plant with a large number of steel panels without any design concept. A bad example of a façade is presented in Fig. 6.15.

The need for shade, openings for air, and the hierarchy of the different quantities of light in the different units of a composting plant allow the architect to develop alternate and interesting façades. The use of local materials can also help the building to blend in more with its surroundings. The architect chooses a constructive grid or an individual proportional grid and the principles of the design for the façade. Successful architecture would normally choose different principles or combinations of principles for different situations. Positive examples of façades of a composting facility are provided in Fig. 6.16.

The following principles can be considered in the design of a façade.

6.16.1. Vertical Division

This emphasizes the vertical elements of the façade. Interruption elements include: emergency staircases, emergency doors, construction elements, and special elements of the façade.

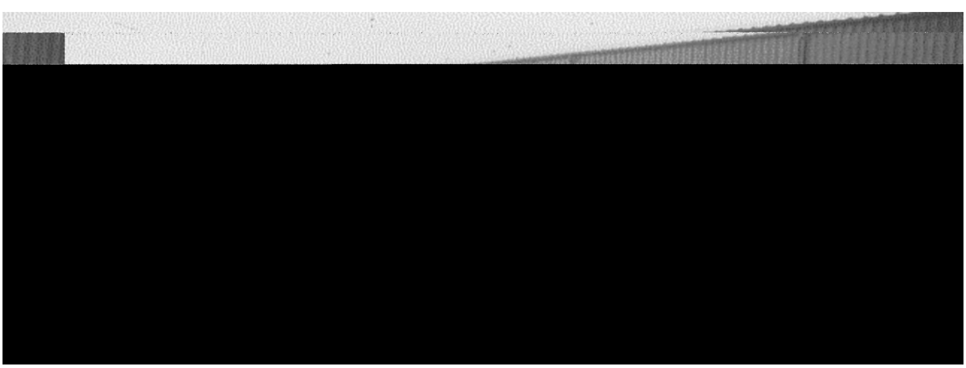


Fig. 6.15. Composting plant, Medemblink, Netherlands (negative example of a façade).

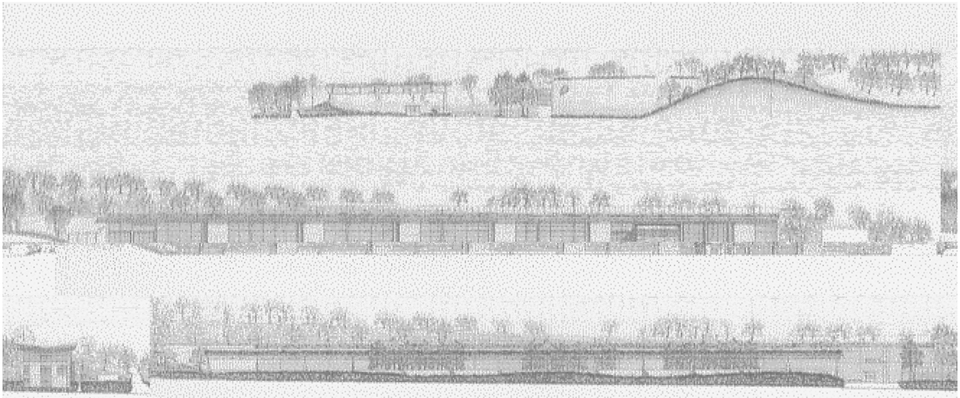


Fig. 6.16. Positive examples of façades of composting plant in Esslingen, Germany.

6.16.2. Horizontal Division

This emphasizes the horizontal lines in the façade, and the division of the building pointing out the different floors or the horizontal grid. Interruption elements include: pedestals, windows, tympanum of the doors, and the horizontal façade cover.

6.16.3. Calm Surfaces

Large undivided surfaces of material may be slightly curved, including single accents by special elements such as windows or air suction openings.

6.16.4. Contrast

This includes division and differentiation of the building by composing different materials and different construction elements for parts of the building and the façades. Materials that can be used include: wood–metal, glass–stone, and concrete–metal.

6.16.5. Construction

This emphasizes that the building construction, columns, and light elements are integrated into the façade.

6.16.6. Motif and Variation

This is development of a form motif for the building and the façade by a material structure, which repeats in different forms.

6.16.7. *Rhythm*

The elements of the façade are added in a rhythm — the grid should also follow this rhythm. The rhythm can be built by the primary structure or secondary structure of the façade.

6.16.8. *Genius Loci*

This includes development of the architecture out of the special situation of a site, the "genius loci," by using material found close to the site or using a form that integrates in a specific situation.

6.17. Influence of Different Composting Systems on Architecture

The equipment available for the area of intensive composting is very different in shape and size, which makes it very important to define the solution early in the design process. It makes an important difference in the design of the building configuration whether the equipment is a composting tunnel, a turning machine, or a composting reactor. It is recommended to prepare the tender for the equipment immediately after the pre-planning phase is completed. The architect must participate in the evaluation of the tenders. Offers for the equipment, which may seem inexpensive, might be more expensive than expected for managing the costs for the basic components and their cover.

From the architectural point of view, composting plants can be divided into three general groups:

1. composting plants with open bay systems;
2. composting plants where the intensive process of the thermophilic phase takes place in boxes, containers, or reactors; and
3. composting plants in an enclosed building with an automatic turning system.

6.17.1. *Open Bay System*

Regarding architecture, composting plants with an open bay system do not integrate well in an industrial or rural zone because there seems to be insufficient odor control. These systems might be interim solutions for composting plants located on a landfill, but generally are not able to fulfill the necessary quality conditions.

6.17.2. *System with Composting Boxes, Containers, or Reactors*

Composting plants in which the intensive process of the thermophilic phase takes place in composting boxes, containers, or reactors might be integrated in rural and industrial zones if the potential odor problems are addressed. There is a special need to address the differences of the systems regarding the process of refilling the containers. Some of these systems perform the process of refilling automatically in an enclosed building, whereas others do not.

Architecturally, an aesthetic solution for the technical form of a steel container or a steel reactor and the cubic forms of the buildings for the pretreatment building, the storage area, and the administration building has to be defined. The problem due to condensation during the thermophilic phase does not impact architectural design because the resistance of containers, reactors, or tunnels to the corrosive condensate must be addressed by the engineer and the entity that supplies the system.

6.17.3. Automatic Turning System

Composting plants in an enclosed building with an automatic turning system integrate well with all urban spaces, because all phases of the composting process take place indoors. Consequently, the configuration of the overall facility consists of a group of buildings, and the buildings do not have to be combined with containers and reactors. The subsequent composting area might take place in the open.

As the thermophilic process takes place inside a building, the architect is responsible for choosing the proper combination of materials to protect the structures from corrosion. It is important for the architect to consider that the condensate from the thermophilic process generally comes into contact with the construction parts of the buildings and equipment. The architect is responsible for the selection of materials and for the construction of the building. On the other hand, the engineer and the company providing the system are responsible for the resistance of the materials selected for the equipment.

6.18. Administration Building

The delivery trucks are controlled, weighed, and registered on truck scales before proceeding to the delivery point. Therefore, the administration office should be situated between the three main points of the plant in order to control the composting process. These areas are: the scales, the pretreatment area, and the processing area.

The administration building can be designed as a single building or be attached to another building. The architectural program of the administration office has to take into consideration the working conditions in a composting plant. Depending on the size and technical specifications of the plant, a staff of 2 to 4 people would be necessary. For these workers, a dressing room with lockers for their change of clothes and sanitary facilities is necessary. The dressing rooms have to be designed in such a way that there are “black and white areas.” White areas are those used by the workers when they first arrive to work to change into their work clothes, and black areas are those where the workers remove their work clothes. These areas should not interfere with each other, so that the white areas do not interfere with those areas where the workers walk with shoes that have been used in the plant. An area specifically used to dry any wet clothes and shoes is normally useful.

The operation of the plant and the supervision of the process can be conducted by means of personal computers and printers. Therefore, it is necessary to have a room as an office and another room, which is used as a laboratory, to perform simple chemical and biological analyses.

The administration and marketing of several plants can be conducted in a central place, where the data are stored, controlled, and transmitted via the Internet.

It might also be useful to include, at the entrance of a plant, a recycling center or a courtyard where private individuals and small enterprises can deliver goods for separate collection. A model garden near the administration building can fulfill two functions: pleasant working surroundings and demonstration of the use of the compost. A pond also is useful to collect rainwater and fulfills the function of biotope.

6.19. Fire Prevention

In accordance with the local authorities, it generally is required to establish a ring road around all of the buildings of the composting plant, but within the property of the facility. This road has to be outside of the so-called “Trümmerschatten” (“rubble shadow”), which means that the road should be built at a certain distance from the building such that in case the building collapses, the rubble from the building would not obstruct the ring road for the fire brigade. The distance from the structures to the road essentially is equal to the height of the façade. It is also necessary to define and plan the water connections for the fire department along the ring road.

In accordance with the local authorities, it is necessary to determine the amount of water that has to be supplied to the site. In case the area is connected to the water supply network, the water pressure and capacity of the network have to be monitored. In most cases, it is necessary to provide water storage. In general, there are two possibilities for water storage:

- a concrete basin above or below ground; or
- a pond.

Every 70 m, there should be the possibility to take water from the water system along the ring. In addition, at certain distances, there should be fire extinguishers available. Emergency exits should be clearly labeled. In addition, an evacuation plan should be developed for the entire facility. The evacuation plan must be placed in a visible area in the administration building, as well as in the plant.

In the event of a fire, a system must be in place to collect the polluted water. A clarifying pond, a process water buffer, the pipe system, or a rainwater tank can be used to collect the polluted water. The floor of the buildings and the open-air spaces should be sloped in order to prevent polluted water from reaching permeable surfaces.

In the event that the delivery, pretreatment, and fine conditioning areas are located inside the same structure, these areas should be separated from the processing building by incombustible materials. However, it is advisable that these areas be located in different structures and that the material be transported from one area to the other by means of covered conveyor belts. Such a wall and the doors or openings in the wall should be constructed so that they offer resistance to the fire for at least 30 min. Along this wall, which defines the fire section, the roof has to be isolated with an incombustible material for a length of 5 m to either side of the wall.

A fire and smoke alarm is to be provided in all areas that contain material or machines that are combustible:

- belts; and
- equipment areas such as in the delivery/pretreatment area and the fine conditioning area.

The fire and smoke alarm system should be automatic and capable of monitoring all the areas on a continuous basis. The system must be connected to the closest fire department or police department.

6.20. Acoustics

The building configuration has to protect other areas from excessive noise. The architect might use the building or excavated soil as barriers.

The construction of walls should consider insulation for noise reduction in the pretreatment area and in the fine conditioning area.

In Germany, there is a guideline known as "Technische Anleitung Lärm" (Technical Instructions against Noise), which defines the limits for noise emissions that are not to be exceeded during the operating hours of the plant and from the traffic coming into or leaving the plant, divided into night and day. The limit during the night is 45 dB, and the limit during the day is 55 dB at the boundary of the plant.

6.21. Lighting

The use of natural lighting is, in most cases, preferable to artificial lighting. In addition, it is important to follow the guidelines associated with minimum requirements for working areas. Examples of intensity of lighting and color by area of the facility are presented in Table 6.6. The information is divided by specific area of the facility.

6.22. Ecological Aspects

Composting plants are considered to be part of the industrial architecture. Innovative industrial architecture is based on the so-called "ecological architecture." This means building energy-saving buildings using as few natural resources as possible. The heating

Table 6.6. Intensity of lighting and color by area of the facility

Area	Nominal intensity of light (in lux)	Color of light
Stocking area	100	Neutral white, warm white
Pretreatment area	100	Neutral white, warm white
Controlling places	750	Neutral white, warm white
Composting area	50	Neutral white, warm white
Fine conditioning	100	Neutral white, warm white
Office rooms	300–500	Neutral white, warm white
Lockers, sanitary rooms	100	Neutral white, warm white
Laboratory	250–300	Neutral white, daylight
Workshop	500	Neutral white, warm white

and cooling of the buildings should be conducted with passive and active uses of solar energy. The use of recycled materials and materials of the type that do not damage the water, solid, and air resources is mandatory. The technical facilities of the buildings should consider using heat pumps, solar heating and cooling, solar cells, and all of the new technical possibilities that we still cannot imagine, but technology will develop in the future. We should rely on architectural excellence regarding a sustainable development of our societies.

6.23. References

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Chapter 7

Quality and Agronomic Use of Compost

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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, 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 m^3. 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 m^3, we also state that, given that 2 μg are 0.009651 μmol of Pb, i.e., 58.14×10^{14} 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 1.445343×10^{14}, 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 1.445343×10^{16}, 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 1.445343×10^{16} 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

a.	Simple or complexed ions in soil solution
b.	Exchangeable ions
c.	Linked to organic matter
d.	Occluded and co-precipitated with oxides, carbonates, and phosphates or other secondary minerals
e.	Ions in the crystalline lattices of primary minerals

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 CO_2, NH_4^+, SO_4^{2-}, and 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 $NaOH/Na_4P_2O_7$ 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 H_2SO_4 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 (C_{org}) in compost samples can be determined according to Springer and Klee (1954). Total extractable carbon (C_{extr}) and humic and fulvic acids carbon (C_{HA+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:

$$\text{Humification rate (HR) percent} = (C_{HA+FA} \times 100)/C_{org}$$
$$\text{Humification index (HI)} = C_{\text{not humified}}/C_{HA+FA} = (C_{extr} - C_{HA+FA})/C_{HA+FA}$$

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 $NaOH/Na_4P_2O_7$ 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 = area under peak/(latent heat of fusion per gram $\times$ 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 % 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 7.2. Distribution of heavy metals in different types of wastes

Cadmium	Ferrous materials; dusts; leather; cardboard; paper
Chromium	Leather; ferrous materials; dusts; textiles
Nickel	Ferrous materials; glass; dusts; ceramic residues
Lead	Wood; dusts; heavy plastics; leather; ceramics
Zinc	Wood; rubber; ferrous materials; dusts; textiles

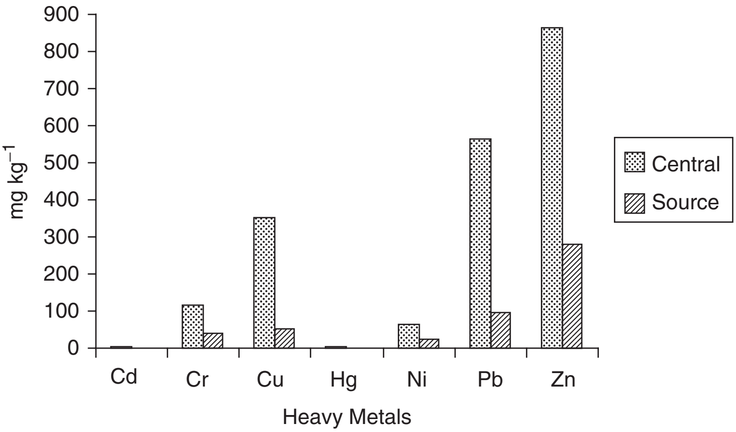

Fig. 7.1. Effects of different contaminant separation methods on the heavy metal content of compost (Richard and Woodbury, 1994).

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 (Petruzzelli 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 7.3. Complexes between organic matter and heavy metals

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
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
c.	Soluble organic matter, which forms insoluble salts reacting with the metals

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

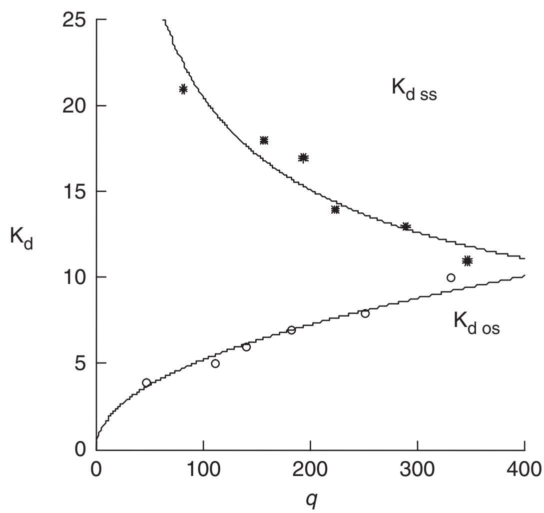

Fig. 7.2. Pattern of Ni distribution coefficient, with ($K_{d\ ss}$) and without ($K_{d\ os}$) sewage sludge, as a function of metal sorbed by the soil q (mol g^{-1}).

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" (Petruzzelli 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; Petruzzelli 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; Petruzzelli 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):

$$q = \frac{q_{\mathrm{m}} KC}{1 + KC}$$

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 (Petruzzelli 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

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

Metal	q_m (μg/g)	K(ml/μg)	R
Zn os	87.1	1.81×10^{-2}	0.9877
Zn ss	152	5.95×10^{-2}	0.9943
Cd os	65.9	0.181	0.9861
Cd ss	84.4	0.119	0.9993

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.

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, 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 integration of the growing media with mineral fertilizers. Peat has stable physico-chemical characteristics and low nutrient values and these characteristics make it difficult to substitute. 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_3^-, SO_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.

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Appendix I. Evaluation of Hazards to the Food Chain[1]

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

[1]Literature 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 dq/dt, the amount that accumulates in the arable layer dq_s/dt, the amount removed by the plants dq_p/dt, and that lost through leaching dq_l/dt, for a given soil layer the following relation applies (Harmsen, 1992):

$$\frac{dq_i}{dt} = \frac{dq_s}{dt} + \frac{dq_p}{dt} + \frac{dq_l}{dt} \tag{1}$$

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 $t \geq 0$:

$$\frac{dq_i}{dt} = k_i \tag{2}$$

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:

$$\frac{d\Delta q_s}{dt} = k_i - \frac{dq_p}{dt} - \frac{dq_l}{dt} \tag{3}$$

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:

$$\frac{dq_p}{dt} + \frac{dq_l}{dt} \prec \frac{dq_i}{dt} \tag{4}$$

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

(I) 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:

$$\frac{dq_\mathrm{p}}{dt} = k_\mathrm{p} \text{ and } \frac{dq_\mathrm{l}}{dt} = k_\mathrm{l}$$

Equation (3) becomes:

$$\frac{d\Delta q_\mathrm{s}}{dt} = k_\mathrm{i} - k_\mathrm{p} - k_\mathrm{l} \tag{5}$$

(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:

$$\Delta q_\mathrm{s} = kC$$

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

The following relations apply:

$$\frac{dq_\mathrm{p}}{dt} = k_\mathrm{p}\Delta q_\mathrm{s} \text{ and } \frac{dq_\mathrm{l}}{dt} = k_\mathrm{l}\Delta q_\mathrm{s}$$

General Equation (3) becomes:

$$\frac{\Delta q_\mathrm{s}}{dt} = k_\mathrm{i} - (k_\mathrm{p} + k_\mathrm{l})\Delta q_\mathrm{s} \tag{6}$$

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:

$$\Delta q_s = \Delta q_{rev} + \Delta q_{irr} \tag{7}$$

and the solubility of the metal is regulated only by Δq_{rev}.

Assuming that the rapidity of transformation of the chemical forms is of the first order according to the equation:

$$\frac{\Delta q_{irr}}{dt} = k_t \Delta q_{rev} \tag{8}$$

where k_t is a constant of velocity (years^{-1}). From Equations (7) and (8), we have general Equation (9) as follows:

$$\frac{\Delta q_{rev}}{dt} = k_i - \frac{dq_p}{dt} - \frac{dq_l}{dt} - k_t \Delta q_{rev} \tag{9}$$

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[2]

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, giberelin, 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; Bouchè, 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

[2]Literature 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 giberelic 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)

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

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.
Source: Benedetti, 1992.
[a] Springer and Klee, 1954.

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 foetida* 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 CO_2,
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)

Sample	Mineral N mg kg^{-1}			Total P (%)	Organic P (%)	Available P_2O_5 mg kg^{-1}
	N–NH_4	N(NO_3 + NH_4)	N–NO_3/N–NH_4			
Cattle manure	7	541	76	0.71	0.35	1.02
Cattle casting	9	1991	220	0.75	0.33	0.97
Pig manure	162	207	0.28	0.76	0.42	0.78
Pig casting	78	2997	37	0.43	0.22	0.48
Sheep manure	11	2622	237	0.69	0.28	0.95
Sheep casting	18	2163	119	0.22	0.26	1.05
Mixed manure A	138	175	0.27	0.54	0.10	0.61
Mixed manure A casting	20	2556	127	1.03	0.39	1.46
Mixed manure B	10	1346	134	0.38	0.08	0.30
Mixed manure B casting	20	1715	85	0.46	0.33	0.31
Cattle manure + cardboard*	155	836	7	0.59	0.06	0.82
Cattle manure casting + cardboard*	111	776	6	0.76	0.08	0.44
Poultry manure + cellulose**	25	56	1	1.97	0.26	0.76
Poultry manure casting + cellulose	19	782	40	0.59	20.23	0.41

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.
Source: Benedetti, 1992.

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 foetida*, 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 foetida* 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[k]

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

Values followed by different letters present significant statistical differences ($P = 0.05$).
[k] q/ha = 100 kg/ha.
*$(NH_4)^2$ HPO_4 in doses of 0.5 tons ha^{-1}.
Source: Benedetti, 1992.

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.

Chapter 8

Bioremediation

G.M. Savage and L.F. Diaz

8.1. Biodegradation by Composting of Toxic Molecules

This chapter describes key features of the application of biological processing to the treatment of toxic or otherwise hazardous organic wastes, and the use of such processing to remediate sites contaminated with hazardous wastes. The emphasis of the discussion is primarily on aerobic composting. The treatment of this type of waste using biological processes is termed "bioremediation." The results and benefits of bioremediation can include reduction in the ultimate amount of mass requiring disposal (e.g., land disposal or incineration), reduction in the hazardous characteristics of the waste (e.g., toxicity), or both. The features discussed in the chapter are: underlying rationale and pertinent principles, applicable composting technology, and the utility of composting as a biotreatment option.

The biological treatment of waste necessarily means that the waste is susceptible to successful decomposition by microorganisms, i.e., microorganisms can utilize the waste as a source of carbon and energy. Thus, the waste must meet the criterion of biodegradability, and the discussion necessarily applies only to the organic portion of a particular material or waste.

The potential of, and justification for, biodegrading toxic organic materials using composting is indicated by the success of land treatment of a wide variety of recalcitrant wastes (Norris, 1980; Brown et al., 1983; Environmental Research and Technology, 1983) and by the successful composting of some toxic materials. One such class of toxic materials is pesticides and herbicides. Investigations on the biodegradability of this class of materials have been a necessary adjunct to investigations on composting. The reasons are primarily twofold: (1) the potential presence of these contaminating compounds in compost feedstocks; and (2) the impact of residual pesticides and herbicides on the quality of the compost end product. Some pesticides have been shown to be readily biodegradable. The degradation of the pesticides diazanon, chlorpyrifos, carbaryl, and 2,4-D has been found to be substantial under several sets of composting conditions (Mount and Oehme, 1981; Racke and Frinke, 1989; Lemmon and Pylypiw, 1992; Regan, 1994; Vandervoort et al., 1997). While some pesticides have been shown to be biodegradable, others have not shown susceptibility to biological processing. The pesticides shown to be the least biodegradable are the organochlorine pesticides.

Certain phthalates have also been shown to be biodegradable. For example, di(2-ethylhexyl)phthalate, a phthalate ester used in the manufacture of several chemical feedstocks (including PVC resins and polyurethanes), has been shown to be biodegradable by *Pseudomonas fluorescens* FS1 when the concentration is less than 50 mg/l (Feng et al., 2002). The half-life of degradation is about 10 days.

Studies have demonstrated that the constituents of oily wastes (e.g., those produced as a consequence of petroleum refining) can be broken down by composting (Cal Recovery Systems, 1985; Savage et al., 1985a,b).

Microbiological investigations involving the degradation of resistant organic materials have provided further evidence and proof of the potential of biologically decomposing recalcitrant substrates (Zobell, 1950; Prince, 1961; Nelson et al., 1973; Mitchell, 1974; De Renzo, 1980; Nyns et al., 1986). Some examples of microorganisms shown to have metabolized resistant organic compounds are given in Table 8.1.

Table 8.1. Microorganisms shown to have metabolized recalcitrant organic compounds

Compound	Microorganism
DDT	*Escherichia*, *Hydrogenomonas*, *Saccharomyces*
Detergents	*Nocardia*, *Pseudomonas*
Dieldrin	*Mucor*
Endrin	*Arthrobacter*, *Bacillus*
Lindane	*Clostridium*
Malathion	*Trichoderma*, *Pseudomonas*
PAH	*Burkholderia*
Phthalate esters	*Pseudomonas*
Phenylmercuric acetate	*Pseudomonas*, *Athrobacter*, *Citrobacter*, *Vibrio*
Raw rubber, hevea latex	*Actinomycetes*, bacteria

Source: Nelson et al. (1973), Feng et al. (2002), and Wong et al. (2002).

Regardless of the indications in the table, it should be emphasized that most of the reported findings resulted from studies that involved a monoculture of a particular microorganism cultured on an idealized carbonaceous substrate under carefully controlled laboratory conditions. The results under field conditions could be less successful. On the other hand, information obtained under idealized conditions is very useful in either the search for or in the selection of the microbial population best suited to serve as "seed," either for starting or for enhancing the composting of biodegradable hazardous wastes.

8.1.1. Principles

The principles that govern the composting of toxic materials are similar to those that govern the composting of more easily decomposed organic substances, such as yard trimmings or food preparation waste. While certain conditions may require modification, the principles are essentially the same as those characteristic of every type of biological waste treatment system. The similarity is readily understood since composting is a biological phenomenon.

The factors of key importance in conventional composting and in hazardous waste composting are microbiology and the factors that characterize the environment of the active microbes.

8.1.2. Microbiology

The microbiology of toxic waste composting is similar to that of conventional composting. The primary differences between the two composting situations are that in toxic waste composting, an enrichment technique is imposed and inoculation is frequent. Consequently, inoculation and enrichment are common in toxic waste composting and seldom used in the composting of conventional organic materials. Inoculation consists of the introduction of microbes capable of breaking down molecules of material usually resistant to microbial attack. Inoculums consisting of indigenous microorganisms are preferable to exotic or "engineered" microorganisms (Kozdroj, 1996). The reason for the use of an inoculum is that certain types of toxic molecules are degradable by only one or a few species of microbes rarely encountered in nature (Rochkind et al., 1986).

Inoculation can be substituted by enrichment (Mitchell, 1974). Enrichment is the technique of establishing conditions that favor the proliferation of microbes capable of using the nutrient elements in the molecules of the substrate. In the case of composting toxic organics, the sole source of nutrient elements would be the molecules of the toxic compounds. Inasmuch as most toxic organic compounds are carbonaceous, carbon is made the limiting element. The effect is that the only microorganisms that will proliferate are those that have access to the carbon in the toxic organic molecule. An alternative to enrichment is the introduction of material likely to contain the required microorganisms. Examples of such materials are composted sewage sludge, garden loam, crop residues, and manures. Recirculation of a small fraction (on the order of 10% by weight) of the output (product) replaces the continuous need for the use of inoculation in an ongoing operation.

8.1.3. Environment

In common with conventional composting, the environmental factors of importance in composting of toxic organic compounds are physical properties, temperature, pH, O_2 concentration, moisture content, and nutrient availability.

8.1.3.1. Physical Properties

Physical properties of concern are geometrical shapes and physical dimensions of the particles composing the substrate. Fundamentally, the smaller the particle size, the more efficient and, therefore, rapid is the process of degradation (Golueke, 1977; Golueke and Diaz, 1980). Practically, however, certain other factors exert a substantial influence. For example, porosity ranks high in importance among these factors. Porosity is largely a function of shape, structural integrity, and size of the individual particles. The influence of these three material characteristics is illustrated by the following example: the permissible dimensions of sawdust particles used as a bulking agent may be only a few millimeters. In contrast, paper particles must be larger than 2.5–10 cm. Municipal refuse used as a bulking agent should have a particle size distribution of 2.5–5 cm (Diaz et al., 1982).

8.1.3.2. Oxygen Concentration

The usual practice is to compost organic wastes in a completely aerobic environment. However, the imposition of an anaerobic phase may be needed in the composting of certain toxic organic compounds, particularly certain halogenated organic pesticides and hydrocarbons (Rose and Mercer, 1968; Epstein and Alpert, 1980; Ghosal et al., 1985; Broholm et al., 1993).

The primary and usual source of oxygen consumed in composting is the atmospheric oxygen (O_2) retained in the interstitial voids of the composting mass. Thus, the mass must be sufficiently porous to accommodate the required volume of O_2 throughout the composting period. In the case of composting toxic organic waste, if it inherently lacks the physical characteristics needed to render it porous (an example would be petroleum tank sludge), a bulking agent should be incorporated into the substrate.

8.1.3.3. Moisture Content

Moisture content becomes limiting to the composting process if it is less than 40–45%. Thereafter, microbial activity is increasingly compromised until it entirely ceases when the content has dropped to about 10%. In practice, if the composting media has low porosity, then the maximum permissible moisture content would be on the order of 45–55%. On the other hand, if the mass has high porosity, the limit could be as high as 85–90%, although 70–80% would be a more judicious level.

8.1.3.4. Nutrient Availability

Nutritional requirements in the composting of toxic materials are the same as those in conventional composting. Thus, the essential elements are carbon, nitrogen, phosphorus, and an assortment of other elements. Nutritional deficiencies are corrected by way of the introduction of the missing element or elements, in the form of a chemical compound (e.g., commercial fertilizer), of an organic waste rich in the missing nutrient, or of a combination of the two. In the case of toxic waste, the probability is that nitrogen would be the missing element inasmuch as most toxic compounds are predominantly carbonaceous (i.e., are hydrocarbons) and devoid of nitrogen atoms. A list of organic wastes that could supply nitrogen if needed is given in Table 8.2.

8.1.3.5. Temperature

In typical practice, temperature of the composting mass is mostly a function of heat generated by microbial metabolic activity. Heat generated by microbial metabolism under proper composting conditions is sufficient to raise the temperature of the composting mass to thermophilic levels. However, the composting mass should be manipulated such that its temperature does not exceed 50–55°C. Microbial activity is inhibited when the temperature exceeds that level. Also, volatilization of hazardous compounds is a matter to be considered if volatile or semi-volatile organics are present in the substrate. Generally, the degree of volatilization is a function of temperature of the mass.

Table 8.2. Nitrogen content of several wastes

Material	Nitrogen (%)	C/N ratio
Activated sludge	5	6
Blood	10–14	5.0
Cow manure	1.7	18
Digested sludge	2–4	—
Grass clippings	3–6	12–15
Horse manure	2.3	25
Night soil	5.5–6.5	6–10
Oat straw	1.1	48
Pig manure	3.8	—
Poultry manure	6.3	15
Raw sewage sludge	4–7	11
Sawdust	0.1	200–500
Sheep manure	3.8	—
Urine	15–18	0.8
Wheat straw	0.3–0.5	128–150

Source: Adapted from Kuter et al. (1985).

8.1.3.6. pH

Theoretically, the pH range most favorable to microbial activity and efficiency is 6.0–7.5. However, practical experience has shown that an initial pH level in the range of 5.5–8.0 usually does not seriously compromise the compost process. In those instances where elevation of pH is deemed prudent or advantageous to elevate a low pH, $Ca(OH)_2$ or any other biologically innocuous alkaline material can be added to the substrate to increase the pH. A decision to increase the pH level should take into consideration the fact that nitrogen loss from the mass accelerates when the pH level becomes too alkaline, i.e., 7.5 or higher. An excessively high pH level can be lowered through the introduction of a non-toxic acidic material [e.g., $(NH_4)_2SO_4$].

8.1.4. Performance and Process Indicators

Indicators of the performance of the composting process for composting toxic materials are similar to those for conventional composting — volatile solids destruction, temperature rise and fall, ratio of O_2 to CO_2, and change in appearance of the composting mass. A parameter peculiar to composting of toxic materials is the reduction in concentration of the toxic compounds. In practice, interpretation of performance is in relation to the stages and time-history of the compost process, i.e., incubation (initial), active (high-temperature), and maturation (curing).

8.1.4.1. Temperature Level

Temperature level and change in the temperature not only are "convenient" performance parameters, they also have a particular significance in terms of the compost process. However, their applicability rests upon the existence of operating conditions such that metabolic heat accumulates within the composting mass. This requirement generally is satisfied in conventional composting practice, and therefore temperature level and its change are useful parameters. General experience indicates that if suitably sheltered from wind and rain, an actively composting mass at least 1 m^3 in volume would be sufficiently large to meet this condition.

The importance and utility of temperature as a performance indicator arises from the fact that an inhibition of microbial activity during the composting process brings about a drop in temperature. The performance parameter aspect is that the inhibition can be accompanied by the development of an unfavorable situation, e.g., malodors. The inhibitory situation could be a low moisture content, lack of oxygen (anaerobiosis), or nutrient deficiency. A continuous gradual decline in temperature indicates the completion of the active stage resulting from cell aging and depletion of readily decomposable substrate. The proper response in case of an inhibitory condition obviously is to make the necessary corrective adjustments. If aging were the cause, the temperature drop would be irreversible and would be indicative of the onset of the "maturation" stage. When the final drop approaches the

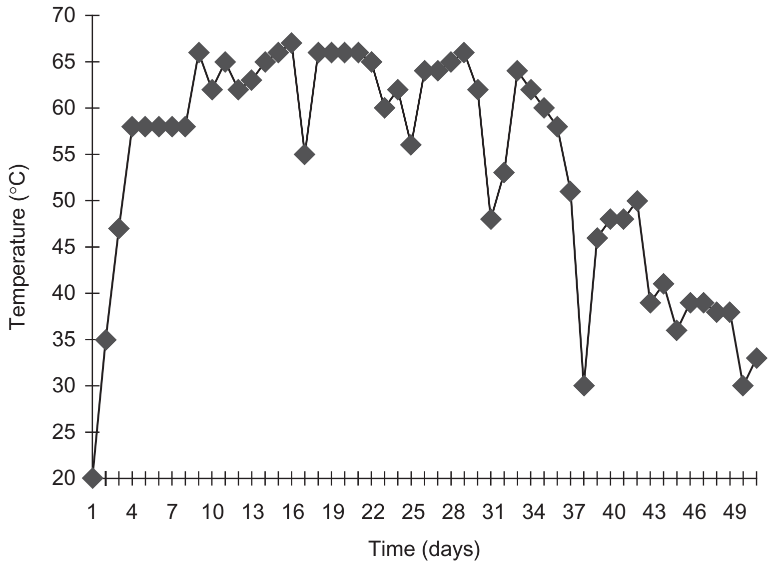

Fig. 8.1. Typical temperature–time-history of a composting mass.

ambient temperature level, the composting mass may be considered to be biologically stabilized. If a toxic compound were the principal source of carbon for the microbial population, the final drop could indicate that the compound has been eliminated or has been transformed into an intermediate form.

A typical temperature–time-history of a composting mass is illustrated by the curve shown in Fig. 8.1. Shown in the figure are the initial acceleration, the "plateauing," and the subsequent gradual decline in rate of heat generation and microbial activity as manifested by shifts in temperature level.

8.1.4.2. Oxygen and Carbon Dioxide Concentrations

The oxygen (O_2) and carbon dioxide (CO_2) levels within the composting mass indicate the level of activity of the microorganisms. Elevated levels of O_2 consumption and of CO_2 evolution indicate rapid metabolic activity and, therefore, rapid decomposition of carbonaceous material. Characteristics, interpretation, and subsequent application of the O_2 and CO_2 levels in the composting of toxic compounds and in conventional composting are, for the greater part, comparable. While data for O_2 and CO_2 levels are lacking for composting of toxic materials, they should be comparable and similar to those reported for conventional composting. Results of tests reported in the literature indicate that the uptake of O_2 ranges from as low as 1.0 to as high as 13.6 mg O_2/g volatile matter/h. Among the reported data concerning approximations of O_2 concentrations are the following: an O_2

pressure in excess of 14% of the total indicates that about one-third of the available O_2 in the air has been consumed. The optimum level of oxygen is within the range of 14–17%. The consensus is that aerobic composting ceases when the O_2 concentration drops to 10% by volume. The CO_2 in the exhaust gas should be between 3 and 6% by volume.

8.1.4.3. Physical Characteristics

Parameters related to physical characteristics of significance in the composting of toxic materials are, for the greater part, similar to those of interest in conventional composting. Physical characteristics of interest are appearance, odor, texture, and particle size. Generally, advancement in the process of decomposition is manifested by improvement in "physical quality," e.g., transition from lighter shades to darker shades (e.g., brown, or "earthen"). Of course, there are exceptions to this general rule; one being that dark shades are usually present in all phases of composting of petroleum sludges.

Some of the more readily perceptible physical characteristics of the composting process are visual and tactile. Visual characteristics include changes in color and overall appearance. Tactile characteristics primarily deal with texture (i.e., "feel") and subsequent changes in texture. Improvement in texture is a reliable indicator, whereas the taking on of a dark color is not. The significance of "overall appearance" arises in part from the relation between appearance and moisture content. Thus, a "dusty" appearance denotes dryness, whereas a damp, glistening surface indicates a moisture content that can range from satisfactory to excessive.

8.1.4.4. Odor

An important compost process indicator is odor, both type and intensity, emanating from the composting mass. The types and intensities of odor emanating from a composting mass reveal shortcomings in operational and environmental factors, as well as deficiencies in the amount of degradation, stability, or quality of the end product. For example, a foul odor usually indicates anaerobiosis and the need to adjust the operating conditions of the process such that the availability of oxygen is increased. If aeration had been inadequate because of excessive moisture, amplifying aeration will dry the composting mass to the extent required for aerobiosis. It should be borne in mind that the acquisition of an earthy odor does not necessarily indicate sufficient decomposition, stability, or maturity. For instance, sufficiency of the degradation of an aromatic toxic organic substance is evidenced by the disappearance of its characteristic odor. Assuming the presence of a microbial population capable of degrading the toxic compounds, the rate and extent of disappearance of the aromatic component are indicators of the efficiency of the compost process. However, the complete loss of the aromatic substance and the attainment of stability of other components of the composting mass are not necessarily coincidental.

8.1.5. Technology

Systems designed to utilize composting in the degradation, or remediation, of a toxic substance may consist of one or more unit processes. In some systems, composting may be the sole unit process; in others, it may be one of two or more constituent unit operations. In the latter case, the function of composting may be to bioremediate objectionable intermediates, or to render them more susceptible to some non-biological process, or to reduce the volume or mass of intermediates destined for final disposal.

Technologies for conventional composting and for composting toxic compounds can each be divided into two broad classes — namely, windrow (open pile) and in-vessel. The following discussion is entirely focused on compost technologies that have been or can be applied to composting of toxic organic materials.

8.1.5.1. Open Pile

The open pile method consists of a simple mass of feedstock prepared with the appropriate environmental conditions. As in conventional composting, the open pile approach can be grouped into two broad groups — turned windrow and static pile. Static-pile composting can be further classified into passive aeration and forced aeration.

Although the terms "pile" and "windrow" are oftentimes used interchangeably, the term windrow is reserved for an elongated pile. In the application of the windrow system (open pile), the upper permissible limit of the height of the piled, or stacked, substrate is that which does not impair the porosity of the stacked material. Consequently, permissible height is a function of the structural and physical characteristics of the individual particles of the substrate. In reality, pile height also is limited by the design of the materials handling equipment. For example, although porosity may remain intact in a windrow that is 3.5 m in height, the materials handling equipment (e.g., turning machine) used may be able to stack the substrate only to a height of 1.5–2 m. With manual stacking and turning, the height might be on the order of 1.5–2.0 m (Golueke and Diaz, 1980). Manual stacking, however, may not be a viable alternative given the fact that toxic compounds may be present.

The proper width of a windrow is the one best accommodated by the method used in stacking the material. In practice, widths usually range from 2 to 3 m. Length is a function of pile arrangement and manipulation, and of site characteristics.

A number of conditions determine which of the feasible cross-sectional configurations of a windrow is appropriate. Among the conditions are meteorology, design and capacity of the materials handling equipment, and method of aeration. Windrows with semicircular or triangular cross-sections are advantageous for climates characterized by abundant or frequent rainfall, because they promote the shedding of water. If heat retention is essential and rainfall is very moderate, a flattened top would be suitable. Windrows with semicircular or triangular configurations are formed when a front-end loader is used for aeration. Most automated, mechanical turners form windrows with a trapezoidal cross-section. The shape of aerated, static windrows is usually trapezoidal or triangular. Ultimately, the important factors in the selection of windrow configuration are the rate of feedstock to be composted, and the capability of equipment used in constructing the piles, in turning them, or in aerating them.

Windrows should always be underlain by a hard, suitably sloped surface, so that runoff and leachate from the processing operation can be collected and properly treated. These measures are especially applicable when toxic materials are concerned. Even in the absence of toxic materials in the substrate, leachate from any composting mass is very concentrated in terms of objectionable components. A hard surface also facilitates construction, turning, and removal of composted material by mechanical equipment.

Because they contain toxic materials, the windrows should be enclosed in a shelter during the active stage. Enclosure is particularly necessary when aromatic toxic compounds are involved. The reason for enclosure is to avoid the release of harmful emissions into the ambient environment, particularly gaseous emissions. The enclosure should be designed such that emissions can be monitored and harmful components can be removed and treated.

There is sufficient evidence that, with few exclusions (e.g., halogenated pesticides), crop residues contaminated with common toxic organic pesticides can be sufficiently and safely treated by windrow composting. Concentrations of contaminants on crop residues usually are relatively low. Moreover, the molecular structure of the contaminants is such that they are vulnerable to physical conditions brought about by the compost process. The key physical conditions include high temperature and moderate pH. In addition, many of the contaminants are susceptible in different degrees to microbial action. Some are photolytic. Lastly, monitoring and exercising careful control of the incoming material and of the operational environment can supply the necessary degree of safety.

The situation is usually different when highly toxic or resistant contaminants are present in the substrate. Unless extensive and complex measures are exercised, the requisite controls cannot be supplied in windrow composting.

Turned Windrow

As discussed earlier, "turning" is a method of aeration employed in windrow composting. Turning is accomplished by successively tearing down and reconstructing a windrow. The time period between the two operations is only momentary. Turning performs the function of replacing depleted oxygen in the interstitial voids of the windrow. A satisfactory environment for aeration requires a thorough agitation of the material and avoidance of compaction during the reconstruction of the windrow.

Required frequency of turning is a function of the magnitude of total interstitial O_2 (or air) and its rate of depletion. Provided that other conditions are not limiting, the rate of O_2 depletion is determined by the degree of microbial activity. Inasmuch as interstitial air can be displaced by water in the substrate, the moisture content of the substrate affects the volume of the interstitial air mass. Therefore, moisture content of the substrate can be an important contributing factor in the determination of the required frequency of turning. As a result, moisture content becomes a factor governing turning frequency, along with the O_2 requirement.

Several versions of automated turning equipment are on the market (Golueke, 1977; Golueke and Diaz, 1980; Diaz et al., 1982; Chiumenti et al., 2005). A feature of most models is a combination of a rotating drum equipped with protuberances and a complementary mechanism that shapes or facilitates the shaping of the pile. The rotating drum effectively agitates the composting material, and the shaping mechanism reconstructs the windrow in one pass through the windrow. Another type of turner uses a front-end revolving auger to both aerate and reconstitute the windrow in a single pass.

Static-Pile Systems

As mentioned previously, static-pile systems are categorized as passive or forced air, based on the method of aeration.

Passive Aeration The fundamental aeration processes in passive aeration are diffusion at the surface of the pile and natural convection within the windrow. The contribution made by diffusion to aeration is minor and is limited to the outermost 10- to 30-cm layer of the windrow, and even less intrusive if the process design includes an insulating layer of material on the outside surface of the substrate.

Natural convection within the pile occurs due to the temperature differential between the composting mass and the ambient air, i.e., the "chimney effect." As the temperature of the evolving gases within the composting mass begins to rise because of the heat generated by the increasing microbial activity, the cooler, higher density ambient air is drawn into the composting mass to replace the rising, lower density product gases, and is subsequently heated. This phenomenon produces a "draft" within the windrow. Windrow design and construction are not discussed in this subsection because they are identical with those for forced aeration, except that fans are not involved. The principal difference is the absence of fans in passive aeration.

Passive aeration was practiced in some cases in the 1950s and 1960s. The general experience with passive aeration has been less than satisfactory except for certain feedstocks or in those cases where the length of processing time is not a constraint. Static aeration is still practiced in some cases (Mathur et al., 1990).

Forced Aeration In the case of forced aeration, turning, as a method of aeration, is replaced by inducing the flow of air through the pile using an electromechanical blower or fan. Depending on a number of parameters and conditions, negative pressure (suction) or positive pressure (blowing) induced within the pile may be used to secure aeration of the composting mass. Under some circumstances, negative and positive aeration may be alternated at certain intervals to achieve adequate aeration of the pile, or for other reasons of process control.

WINDROW CONSTRUCTION In forced-aeration composting design, the construction of windrows is commonly implemented upon a perforated base through which air is forced into or drawn from the pile (U.S. Environmental Protection Agency, 1979). The Beltsville approach (Wilson et al., 1980) uses embedded, perforated air piping in a bottom layer of wood chips or other comparable material. The windrow is constructed upon this layer. Among the variations of the Beltsville method is the sequencing of positive and negative modes of air pressure, as mentioned previously. Another variation involves treating the exhaust gas by passing it through a biofilter system. A third variation is the addition of an outer layer of fully composted material or wood chips that serves the functions of insulating the pile and of a biological treatment layer for controlling emissions of odors and volatile organic compounds.

AIR INPUT RATE The necessary air flow rate induced in the composting mass is a function of the goal of the processing operation. The goal may be solely to supply the O_2 required to maintain aerobiosis. On the other hand, the objective may be multifold — namely, not only to maintain aerobiosis, but also to control the interior temperature of the windrow and lower the moisture content. Consequently, the required air input rate becomes a function of the O_2 demand, windrow temperature, substrate moisture content, and of the attendant interrelationships.

The necessary air flow for aerobiosis alone can be gleaned by the following example reported in the literature (Diaz et al., 1982): the substrate was 40 metric tons of a mixture of sludge cake and wood chips (bulking agent) stacked in a windrow that was 12 m in length, 6 m in width, and 2.5 m height. Diaz et al. state that an air input rate of approximately 5 m^3/min was sufficient to ensure an oxygen concentration of 5–15%. Findings made in other studies reported in the literature indicate the amounts involved when the processing objective is multifold. For example, studies (Finstein, 1983; Kuter et al., 1985) have shown that drying and destruction of volatile solids are greatest at high aeration rates, e.g., 22 $m^3/(h \cdot \text{metric ton})$ initial wet weight, and relatively low composting temperatures, i.e., lower than 55°C.

Summary of Key Requirements

The requirements described in this section are those that are key to successful composting, and they represent the ideal set of conditions. Foremost among the conditions in the set is porosity of the substrate. Porosity depends to a large extent on these three characteristics of the substrate: (1) granular texture, (2) a particulate structure resistant to compaction, and (3) uniform particle size that is less than about 5 cm in any dimension. Moreover, the moisture content of the substrate must be such that the volume of pore space not occupied by water is sufficient to accommodate the volume of air needed to meet the microbial O_2 demand.

Inability to meet the porosity requirement generally rules out the use of the static-pile approach for composting inadequately "bulked" substrates, e.g., oily waste sludges.

8.1.5.2. In-Vessel Systems

The in-vessel technologies currently used in the composting of toxic waste generally are an adaptation of the in-vessel technology developed for composting conventional (i.e., non-hazardous) organic wastes. The principal goal in in-vessel design is the attainment of adequate aeration. The aeration is accomplished by way of agitating the contents of the vessel (reactor), or by forcing air through the contents, or both. Agitation is achieved by any of the following methods: (1) "tumbling" the composting material, (2) dropping it from one level to a lower level, and (3) stirring the material.

One of the classifications of in-vessel technologies reported in the literature groups the types of reactors into the following four general categories: (1) agitated bed reactors, (2) silo reactors, (3) tunnel reactors, and (4) enclosed static-pile reactors (Anderson et al., 1986). Agitated bed types of reactors may be further divided into designs that use rectangular reactors and types that involve the use of circular reactors.

A second classification of in-vessel systems reported in the literature divides types of reactors into the following three categories with respect to the general flow of material through the reactor: vertical, inclined, and horizontal (Golueke and Diaz, 1980). The systems are further divided on the basis of the condition of the mass in the reactor and on the method of agitating the composting mass.

There are primarily two disadvantages in the utilization of in-vessel systems. The first is high capital and maintenance cost. The second is the general lack of the operating experience and data whereby candidate systems can be evaluated and compared. Nevertheless, in-vessel composting may be the only possible or feasible alternative in many situations. For example, in-vessel technology has shown promising potential in the treatment of dangerous wastes such as highly toxic aromatic substances and explosive propellants (Brown et al., 1995; Spongberg and Brown, 1995; Spongberg et al., 1996).

8.2. Decontamination of Soils

Certain biological processes can be used to decontaminate soils or to treat hazardous organic compounds that are commonly found in contaminated soils. In the latter case, an option is to remove the organic compounds from the contaminated soils by the use of chemical or physical processes (e.g., leaching or air stripping of contaminated soils to concentrate hazardous organic constituents), and subsequently to biologically process them. Depending on circumstances, successful treatment of contaminated soils may require the use of several unit operations, of which biological processing may be one. The application of composting and other biological methods of treatment to soil decontamination are discussed in this section by way of several examples.

Composting has been demonstrated to be moderately effective in remediating soil contaminated with polychlorinated biphenyls (PCBs). Field studies (Michel et al., 2001) found that, in soil contaminated with 16 mg/kg PCBs, composting of the soil with yard trimmings yielded 40% loss of total PCBs. Degradation was preferential for 1 to 3 chlorinated PCB congeners, with little or no degradation of congeners having greater than 4 chlorine atoms per biphenyl. Laboratory research has pointed out that the limitation in composting PCBs is the lack of ability of microorganisms to utilize PCBs exclusively as a carbon source for metabolic energy (Abramowitz, 1990; Boyle et al., 1992).

Since contaminated soil may lack adequate nutrients for bioremediation, yard trimmings represent a viable source for providing them.

Laboratory experiments have shown that the remediation of soil contaminated with diesel oil can be enhanced using previously remediated, contaminated soil as an inoculum (Hwang et al., 2001). The remediated soil contributes acclimatized, indigenous microorganisms. The concentration of total petroleum hydrocarbons in soil spiked with 10,000 mg/kg diesel oil exhibited a 98% decrease over a 30-day period. In the 3-L experiments conducted in a water bath at 20°C, the optimum ratio of contaminated soil to remediated soil was found to be 1:1.

In this example, a treatment system was designed as an ancillary process to minimize the emissions of volatile aromatic hydrocarbons generated by landfarming of petroleum wastes. The problem of uncontrolled volatilization of volatile petroleum compounds can be avoided by removing the volatile aromatics prior to land treatment. Removal can be accomplished by way of in-vessel composting (Spongberg and Brown, 1995; Spongberg et al., 1996). Emissions from the in-vessel reactor can be trapped and treated such that the aromatics are destroyed, for example, in chemical reactors or biofilters.

A two-stage bioreactor has been shown to be effective in treating solutions containing TCE (Tschantz et al., 1995). The system would have application in the treatment of TCE-contaminated groundwater. Rates of reduction were in the range of 90–93%, inlet concentrations of TCE were in the range of about 3–10 mg/L; hydraulic retention times were in the range of 4.5–6 h.

A proprietary biological processing system has been designed to treat acetic and acetylsalicyclic acids and benzene (Parkinson, 1996). The treatment process is described as "advanced fluidized composting" by the developers; but is "composting" only in the broadest sense of the term. Operation of the system consists of feeding groundwater contaminated with the acids and benzene into a reactor vessel containing a slurry of thermophilic bacteria, which breaks down organics at an operating temperature of 45–65°C. A part of the biomass in the composter tank is continuously removed and fed into a chemical treatment tank, in which it is oxidized to make it amenable to further biological treatment in the composter tank.

The final example of treatment addresses the utility of biological processing to reduce the mass of contaminated soil requiring treatment, and subsequently requiring final disposal. In this example, radionuclides (strontium and cesium) are removed from soils contaminated with them by assimilation into cultivated plants. The contamination is a result of "fallout" from atomic bomb testing and nuclear reactor accidents. Substantially large arable land areas have been contaminated in this manner. The task of remediation is complicated and formidable, not only as a result of the large areas involved, but also due to the tightly bound Sr (strontium) and Ce (cesium) in the upper 10–15 cm of soil. However, it also is known that these elements can be and are removed from the soil and taken up by plants growing on the layer. Consequently, one method of remediation would be to cultivate rapid-growing plants on the contaminated soils, then harvest and compost the plants, and subsequently incinerate the composted residue and dispose of the resultant ash in a nuclear waste repository (Entry et al., 1996). The role of biological processing would be to reduce the mass of the harvested material destined for incineration.

8.3. Conclusions

Substantial documentation exists with regard to composting of hazardous organic compounds. However, research and development efforts appear to substantially exceed the number of commercial applications of the technology. Consequently, the magnitude of the full potential of composting as a means of bioremediation has not as yet been fully ascertained. The potential benefits of bioremediation include reduction in the amount of mass ultimately requiring disposal and reduction in hazardous characteristics (e.g., toxicity) of the waste.

Biological treatment, including composting, has been shown to successfully degrade a number of toxic or otherwise hazardous compounds. Accordingly, the potential of composting would be especially applicable to the remediation of biodegradable pesticides and of solid wastes and soils contaminated with hazardous organic materials. The potential extends to liquid and semi-liquid hazardous wastes that have been adequately mixed with other materials (bulking agents) to achieve the necessary moisture content and degree of porosity of the resulting mixture. For example, use of bulking agents makes it feasible to compost oily wastes. However, composting by itself may not be an effective method of management for all types of organic hazardous wastes. For example, some chlorinated hydrocarbons decompose very slowly under aerobic composting conditions.

In practice, biotreatment of hazardous waste oftentimes will involve a number of complementary unit operations in order to offer optimum processing, including physical and chemical processing, and materials handling arrangement. Additionally, the phase of the substrate processed biologically may be aqueous, solid, or semi-solid (e.g., industrial sludges), or some combination of these.

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Chapter 9

Pathogenic Agents

R. Böhm

9.1. General Remarks

Recycling of biological wastes by aerobic or anaerobic biotechnological treatment is necessary to protect the environment and to save natural resources. The recycling process may be conducted either: (1) in large-scale plants operated mostly in urban industrial areas, or (2) in small plants operated primarily in the rural environment to improve the farmer's income. Municipal solid wastes, sewage sludge, and other organic sludges may contain different kinds of pathogens that are infectious to several species of animals and plants, as well as to humans. The origin and nature of organic wastes and the different types of sludges always cause hygienic risks in storage, collection, handling, processing, and utilization. These risks exist if the organic wastes are collected and processed via source separation (biowastes), if they are collected mixed with other wastes from households or relevant processing industries, if they are generated in the treatment of industrial or municipal wastewater, or if the sludge results from industrial processing of other organic materials. Generally, three main types of risks are associated with recycling of organic wastes:

1. occupational health risks;
2. environmental risks; and
3. risks associated with product safety.

Therefore, hygienic principles must be followed in the collection, transportation, processing, storage, and distribution of such materials.

Occupational health risks exist in small as well as in large-scale plants; however, this is not the subject of this book and more details on occupational health risks may be found in other publications (Hickey and Reist, 1975; Grüner, 1996; Böhm et al., 1998). Environmental risks and risks concerning epidemiological pathways closed via contaminated products, as well as measures that can be adopted against such risks, will be dealt with in this chapter, along with relations to the pathogens involved and to the different epidemiological situations that can be expected under the given conditions. The information in Table 9.1 summarizes the main epidemiological risks associated with recycling solid and liquid organic wastes.

The risks related to the different raw materials are mainly defined by the presence of certain organisms and their properties. This will be covered in more detail in other sections of this chapter. Generally, they can be divided into those causing phytohygienic risks and those related to human and animal health. The data in Table 9.2 provide a survey concerning the hygienic relevance of some organic wastes originating from households.

Table 9.1. Epidemiological importance of processed wastes and residuals, and of the resulting products

A.	**Direct transmission to farm animals**
	Contamination of meadows
	Introduction of pathogens by storage and processing close to susceptible animals
	Aerogenic transmission by spreading the materials onto farm land
B.	**Direct transmission to humans**
	Handling of contaminated products in the household
	Occupational exposure to contaminated products
	Accidental transmission to immune-compromised persons
C.	**Indirect transmission to farm animals**
	Via feed from contaminated sites
	Via living vectors
D.	**Indirect transmission to humans**
	Via introduction of zoonotic agents into the food chain
	Via food contaminated by living vectors
E.	**Introduction into the environment**
	Generation of carriers in the fauna
	Introduction of undesired properties into the microflora

Table 9.2. Hygienic relevance of different biological wastes originating from households

Type of waste	A	B
Meat-leftovers (raw or insufficiently heated)		
– meat cuttings, tendons, rinds, etc.	+	–
Food of animal origin		
– egg shells	+	–
– several meat and dairy products	+	–
– raw milk products	+	–
– leftovers from fish and shellfish	+	–
Other wastes (animal and man)		
– dirty packing material for meat and products of animal origin	+	–
– used litter and wastes from pets	+	+
– used paper handkerchiefs and sanitary pads	+	–
– diapers	+	–
Household wastes from		
– potatoes	–	+
– carrots	–	+
– onions	–	+
– tomatoes	–	+
– cucumbers	–	+
– salad	–	+
– cabbage	–	+
– beans	–	+
– cut flowers	–	+
– balcony and indoor plants	–	+
Garden wastes		
– boughs and plant material	–	+
– fruits	–	+
– dead leaves and lawn trimmings (fecal contamination)	+	+
Other wastes (plant origin)		
– paper	–	–
– paperboard	–	–
– organic packing material (e.g., wood wool)	–	–

A — May contain pathogens of man and animals.
B — May contain plant pathogens and/or weed seeds.

The data in the table show that pathogens for humans and animals are not always limited to materials from warm-blooded individuals, but that they can originate from plant materials as well.

A relatively large number of pathogens are found in solid and liquid organic wastes; the most prevalent are bacteria, viruses, fungi, and parasites. A brief discussion of each type follows.

9.2. Bacteria

Bacteria may propagate in the raw materials during collection, transport, and storage and they are involved in the composting process itself. In the latter case, especially in thermophilic processes, the bacterial pathogens are more or less reduced in number. It has to be considered then that they often propagate in the raw materials before being processed. This increases the risk and leads to a general contamination of the collected materials during transport. If sludges from wastewater treatment (biosolids) are composted, nearly all gut-related pathogens may be found, while some materials of industrial origin are nearly sterile if they were heated during processing.

A compilation of bacterial pathogens of humans, animals, and plants that may be present in organic wastes is presented in Tables 9.3 and 9.4. Presence of bacterial pathogens alone has nothing to do with the resulting risk of infection. Transmission via the environment and the resulting route of infection must be a factor in the epidemiology of the resulting disease. The most important pathogens in this connection are *Salmonella* spp.; others, like *Listeria* or *Clostridia*, may also be present in the material, but they are also present in the soil and therefore are of secondary importance if the product is used as a soil conditioner.

9.3. Viruses

Several viruses of plant origin may be present in the raw materials (Table 9.5), as well as gut-related viruses of animal and human origin. Special risks are connected with viral

Table 9.3. A selection of obligatory and facultative pathogenic bacteria that can be isolated from biological and household wastes

Obligatory pathogens	Facultative pathogens
Salmonella spp.	*Escherichia*
Shigella spp.	*Klebsiella*
Escherichia coli (enteropathogenic strains)	*Enterobacter*
Pseudomonas aeruginosa	*Serratia*
Yersinia enterocolitica	*Citrobacter*
Clostridium tetani	*Bacillus cereus*
Clostridium perfringens	*Proteus*
Clostridium botulinum	*Providencia*
Bacillus anthracis	
Listeria monocytogenes	
Vibrio cholerae	
Mycobacterium spp.	
Leptospira spp.	
Campylobacter spp.	
Staphylococcus	
Streptococcus	

Table 9.4. A selection of plant pathogenic bacteria and viruses (adapted from Menke, 1992)*

Pathogen	Susceptible plant	Type
Xanthomonas campestris	White cabbage, turnip cabbage, Swede cauliflower	B
Pseudomonas marginalis	Salad, endive	B
Pseudomonas phaseolicola	Beans	B
Pseudomonas lacrimans	Cucumber	B
Pseudomonas tabaci	Tobacco	B
Corynebacterium michiganense	Tomatoes	B
Corynebacterium sepedonicum	Potatoes	B
Erwinia phytophthora	Potatoes, carrots	B
Erwinia amylovora	Pomaceous fruits, flowers	B
Agrobacterium tumefaciens	Various hosts	B
Potato virus Y	Potatoes, tobacco, tomatoes	V
Potato virus X	Potatoes, tomatoes, tobacco, paprika, eggplants	V
Aucuba virus	Potatoes, tobacco, tomatoes	V
Tobacco ring spot virus	Potatoes, tobacco, beans, cucumber	V
Rattle virus	Potatoes, tobacco	V
Tobacco mosaic virus	Tobacco, tomatoes, paprika	V
Tobacco necrosis virus	Tobacco, beans	V
Horse bean mosaic virus	Horse beans, peas	V
Pea mosaic virus	Peas, horse beans	V
Bean mosaic virus	Beans, runner beans	V
Yellow bean mosaic virus	Beans, peas	V
Cauliflower mosaic virus	Several cabbage species	V
Cucumber mosaic virus	Cucumber, melon, pumpkin, spinach, peas, beans, salad, tomatoes, celery	V
Aucuba mosaic virus	Cucumber, melons	V
Cabbage ring spot virus	Cauliflower, white cabbage, horseradish, spinach, tobacco, rhubarb, flowers	V
Lettuce mosaic virus	Salad, endive	V
Beet mosaic virus	Spinach, root beets, leaf beets, peas	V
Onion mosaic virus	Onions, leek	V

B — Bacteria.
V — Viruses.
*More details about transmission and resistance may be taken from the original paper, which also contains information concerning parasitic nematodes and weed seeds.

causative agents of animal diseases such as Foot and Mouth Disease (FMD), which may be present in meat and meat products if the animals had been slaughtered before showing clinical signs of illness. In sludges from wastewater treatment or in other wastes with fecal contamination, hepatitis A virus, rotaviruses, and caliciviruses have to be taken into account as emerging pathogens.

Table 9.5. Selection of viral pathogens that may be present in biological wastes from households and from municipal sources

Groups of viral pathogens of general importance	Viral pathogens of special veterinary importance
Enterovirus	African Swine Fever (ASF) Virus
Poliovirus	Aujeszky Disease (AD) Virus
Coxsackievirus A	Classical Swine Fever (CSF) Virus
Coxsackievirus B	Foot and Mouth Disease (FMD) Virus
Echovirus	Swine Vesicular Disease (SVD) Virus
Adenovirus	Newcastle Disease (ND) Virus
Reovirus	Avian Influenza (AI) Virus
Hepatitis A virus	
Rotavirus	
Astrovirus	
Calicivirus (Norwalk agent)	
Coronavirus	
Parvovirus	

9.4. Fungi

Fungi present in wastes and materials used for composting are mainly of interest from the point of view of occupational health and phytohygiene. From the species pathogenic to warm-blooded animals and humans in Europe, mainly *Candida albicans* and *Aspergillus fumigatus* have to be mentioned in this connection. For plants, a variety of species are important pathogens; well known in this framework is *Plasmodiophora brassicae*. A selection of relevant plant pathogenic fungi is given in Table 9.6.

9.5. Parasites

The presence of parasites or their infective stages in wastes or residues of plant, animal, or human origin depends on the nature of the wastes and the level of pretreatment. Parasites are of veterinary and medical importance if the raw materials used for composting are generated in wastewater treatment facilities or in slaughterhouses (e.g., contents of the digestive tract) and, in general, if the wastes are of fecal origin or contaminated with fecal matter. Some of the most important parasites of epidemiological relevance are listed in Table 9.7. From the protozoal ones, *Cryptosporidium parvum* seems to be the most relevant, while eggs of *Ascaris* species of humans and animals are the most important metazoic parasites. Parasites at large are not only important as pathogens, they may also be a risk factor as vectors in transmission of diseases from wastes to susceptible populations (e.g., by flies and cockroaches).

Table 9.6. A selection of plant pathogenic fungi (adapted from Menke, 1992)

Pathogen	Susceptible plant
Plasmodiophora brassicae	Cabbage
Phoma apiicola	Cabbage
Peronospora brassicae	Celery
Peronospora spinaciae	Spinach
Peronospora destructor	Onions
Marssonina panattoniana	Salad
Sclerotinia minor	Salad
Botrytis cinerea	Salad
Bremia lactucae	Salad, endive
Cercospora beticola	Turnip
Aphanomyces raphani	Radish
Alternaria porri	Carrot
Septoria apii	Celery
Albugo tragoponis	Scorzonera
Albugo candida	Horseradish
Turburcinia cepulae	Onions
Sclerotium cepivorum	Onions
Alternaria porri	Carrots
Botrytis allii	Onions
Uromyces appendiculatus	Beans
Mycosphaerella pinodes	Peas
Ascochyta pinodella	Peas
Erysiphe polygoni	Peas
Cladosporium cucumernum	Cucumber
Sclerotinia sclerotiorum	Cucumber
Septoria lycopersici	Tomatoes
Alternaria solani	Tomatoes
Didymella lycopersici	Tomatoes
Rhizoctonia solani	Potatoes
Phytophthora infestans	Potatoes, tomatoes
Synchytrium endobioticum	Potatoes
Verticillium albo-atrum	Potatoes

Table 9.7. A selection of parasites that can be expected in organic wastes from humans and animals of fecal origin

Protozoa	Cestodes	Nematodes
Cryptosporidium parvum	*Taenia saginata*	*Ascaris lumbricoides*
Entamoeba histolytica	*Taenia solium*	*Ancylostoma duodenale*
Giardia lamblia	*Diphyllobothrium latum*	*Toxocara canis*
Toxoplasma gondii		*Toxocara cati*
Sarcocystis spp.		*Trichuris trichiura*

Table 9.8. A selection of plant pathogenic nematodes (adapted from Menke, 1992)

Species	Host plant	Survival data
Ditylenchus dipsaci	Root beets, leaf beets, kohlrabi, carrots, potatoes, peas, beans, onions, celery, cucumber, salad, spinach, strawberries	Plant residuals and soil: up to 2 years
Ditylenchus destructor	Potatoes	No data
Heterodera schachtii	Root beets, leaf beets, kohlrabi, cabbage, celery, radish, spinach	Soil: larvae up to 1 year Soil: cysts up to 6 years
Heterodera rostochiensis	Potatoes, tomatoes	Soil: larvae up to 9 months Soil: cysts up to 7 years
Heterodera goettingiana	Peas	No data
Pratylenchus pratensis	Root beets, leaf beets, carrots, potatoes, tobacco, peas, onions, chives, cabbage, salad, horseradish, radish	No data
Aphelenchoides parietimes	Carrots, potatoes, onions	No data
Aphelenchoides ritzemabosi	Tobacco, onions	Soil: 4 months
Aphelenchoides avenae	Carrots, onions	
Meloidogyne spp.	Root beets, carrots, potatoes, tobacco, peas, beans, onions, celery, cabbage, endive, cucumber, salad, horseradish, parsley, rhubarb, scorzonera, spinach, tomatoes	Soil: *M. hapla* over 6 months

Plant pathogenic parasites must also be considered, even if some of them are highly specialized on certain plants, which limit their epidemiological importance. Cyst-forming nematodes are the most relevant because these cysts may survive in the soil for several years. Roots and other soil-containing materials used in composting may contain such transmissible stages; more details can be obtained in the literature, such as in Menke (1992). A selection of relevant nematodes is listed in Table 9.8.

9.6. Hygienization

Most countries in the world, including most member states of the European Union, do not have legal regulations defining the hygienic requirements for finished compost. In most cases, indirect parameters, e.g., maturity of the product, frequency of turning of windrows, temperature–time relationships, have to be kept voluntary or in the framework of quality networks. Sometimes, only recommendations or legal demands are given by defining the particle size, minimum temperature, and exposure time, which are insufficient if they are not based on validation experiments or scientific investigations. A typical example is the requirement for composting in a reactor requiring a 12 mm particle size combined with an exposure time of at least 1 h and a temperature of at least 70°C, as set forth in the European animal by-product regulations (EC, 2002), which is not covered by any validation experiment.

There is no doubt that according to the state of science and technology, a composting process if properly applied can inactivate relevant pathogens and weeds. Therefore, sometimes recommendations are given on how to operate the composting process in order to achieve hygienic safety of the product. Such strict recommendations may be: "Composting plants shall operate with the material at a moisture content of 45–50% and a pH of about 7. If the facility uses windrows, the exposure time shall be at least for a period of 2 weeks at 55°C. If the facility uses in-vessel technology, the exposure time will be for a period of 1 week at 65°C." From a scientific point of view, other combinations of temperature and exposure time will lead to sufficient inactivation of the target organisms, since those are mainly vegetative bacteria, viruses, eggs of parasites, or similar transmission stages and seeds. Even spores of *Bacillus anthracis* can be inactivated under certain circumstances, as shown by Miersch (1975). Until now it is not definitely clear if transmissible spongiform encephalopathies (TSE) agents could be inactivated in composting; more research is needed in order to confirm or disprove the findings of Brown and Gajdusek (1991), indicating that the scrapie agent may survive for more than 3 years in the soil. However, their experimental setup does not appear to be representative of the situation in composting. Nevertheless, inadequate technical design and improper management of the composting process may result in survival and transmission of the pathogens involved; therefore, only treatment in a validated process under steady supervision will lead to a hygienically safe product.

This means that the following strategies may be combined in order to assure hygienically safe utilization of the processed materials:

- validation of treatment (disinfection by chemical, physical, or biological means),
- continuous recording of relevant process parameters (e.g., temperature, pH, exposure time),
- microbiological monitoring of the final product (indicators), and
- restrictions on the utilization of the final product.

The capability of a process to inactivate pathogens causing risks that depend on the raw material cannot be judged simply by analysis of presence or absence of indicators (bacterial, viral, fungal, or parasitic) in the final product.

When only product monitoring is used in order to validate a process, it can provide a false sense of security that the process is able to control the relevant hazards in the final product. Absence of one or all of the mentioned pathogens or indicators in the final product may be caused by several other reasons:

- they were not present in the raw material,
- they were present in the raw material, but in a low concentration (less than 5 log),
- due to ineffective enrichment procedures (e.g., bacteria), re-isolation was insufficient, or
- failure of isolation due to effects of the complicated matrix (e.g., viruses).

Therefore, the possibility of validating a process by input–output analysis of certain indicators is, in principle, possible but under practical conditions a rare event depending on the microbiological properties of the input materials processed and other strategies that must be followed, e.g., process validation with one or more representative test-organism. If either the thermophilic process itself or if an additional thermal treatment shall provide the inactivation of pathogens belonging to the indicated level of thermo- and chemo-resistance, representative test-organisms must be exposed in a similar matrix as that being treated in a suitable test-body in a defined validation experiment. The relevant process parameters must be recorded during the exposure in order to define the technical conditions to be kept for safe inactivation according to the results of the survival experiments. The validation of the treatment with respect to hygienic safety for animals, humans, and, if necessary, plants may be done in several ways. For example, the "German LAGA M 10, 1995" (LAGA-Länderarbeitsgemeinschaft Abfall, 1995) offered a relatively broad approach for solving this problem with respect to composting based on the "ATV" (German Association of Wastewater Experts) recommendations from 1988 for sewage sludge treatment (ATV-Abwassertechnische Vereinigung, 1988). Process safety concerning the inactivation of relevant transmissible agents for humans and animals is validated in two steps. The first step is the validation of the process as designed by the producer of the technical equipment in the basic procedure. The second step involves putting into service validation of a treatment process at the plant with the input material used under practical conditions. In both validation procedures, *Salmonella senftenberg W775* (H_2S negative) is used as a test organism exposed in specially designed test carriers. In such a validation procedure, testing is always done twice, in summertime and in wintertime. This is a very complete and safe system; if due to economic considerations the system should be simplified and only a one-step procedure should be the aim, it must be the one that deals with putting validation into service. A scheme of how this validation could be organized in this case, taking into account the annual throughput of material in the plants, is given in Table 9.9 from the "German Biowaste Ordinance" (1988).

The question of how validation should be performed under practical conditions and which test bodies can be applied is not easy to answer. In biogas plants, mainly two types of test bodies may be used, depending on the test organisms (Rapp, 1995; Böhm et al., 1997). Those test organisms like bacteria, fungi, and parasites type 1 test bodies that can be retained by a membrane filter in a test body filled with liquid, as shown in Fig. 9.1, could be used. Exposure of viruses to a process requires different test bodies. The virus material is adsorbed onto a special filter material and released after exposure by desorption, by washing with a special solution. Such a type 2 test body is shown in Fig. 9.2.

In composting, different approaches are described for bacteria, because a representative amount of raw material can be contaminated directly with the test strain and put into textile sacks protected from mechanical destruction by a perforated metal basket, as shown in Fig. 9.3. This system may also be used for phytopathogenic fungi and viruses (contained in plant tissue), as well as for seeds. Viruses not related to tissue may be exposed in the material, as described above in a type 2 test body.

Table 9.9. Example of a validation and supervision strategy for biogas and composting plants and the resulting products according to the German Biowastes Ordinance (1998)

Investigated parameter	Direct validation of the process	Indirect process supervision	Supervision of the final product
Hygienic safety concerning risks for man, animals, and plants	– Newly constructed plants (within 12 months after opening of the plant) – Already validated plants if new technologies have been invented or if the process has been significantly modified (within 12 months after invention or modification) – Existing plants without validation within the last 5 years before this validation strategy was invented (within 18 months)	– Continuous registration of temperature at three representative locations in the process, responsible for the inactivation of the microorganisms and seeds – Recording of process data (e.g., turning of windrows, moisture of material, starting and finishing data)	Regular investigation of the final product for hygienic safety[b,c]
Number of test trials	Two test trials, at open air composting plants, at least one in winter	Continuous data recording to be filed for at least 5 years	Continuously all over the year at least: – semi-annually (plants with $\leq$3000 tons/acre throughput) – quarterly (plants $>$3000 tons/acre throughput)
Number of test organisms			
Human and veterinary hygiene	One test organism (*Salmonella senftenberg W775*, H_2S negative)	–	No *Salmonella* in 50 g product detectable
Phytohygiene	Three test organisms (*Plasmodiophora brassicae*, tobacco mosaic virus, tomato seeds)	–	Less than 2 seeds capable of germinating and/or reproducible parts of plants in 1 l of product

(*continued*)

Table 9.9. Example of a validation and supervision strategy for biogas and composting plants and the resulting products according to the German Biowastes Ordinance (1998) — *Cont'd*

Investigated parameter	Direct validation of the process	Indirect process supervision	Supervision of the final product
Number of samples		–	Throughput of the plants in tons/acre:
Samples per test-trial:			
Human and veterinary hygiene	24[a]		1. ≤3000 (6 samples per year)
Phytohygiene	36[a]		2. >3000–6500 (6 samples per year plus one more sample for every 1000 tons throughput)
			3. >6500 (12 samples per year plus one more sample for every 3000 tons)
Total	60		

[a]At small plants half the number of samples (≤3000 tons/acre).
[b]Every statement concerning the hygienic safety of the product is always based on the result of the supervision of the final product together with the result of the validation of the process.
[c]Every sample is a "mixed sample" (about 3 kg) based on five single samples of the final product.

Fig. 9.1. Type 1 test bodies for exposure of contaminated liquid substrates in biogas plants with bacterial test strains.

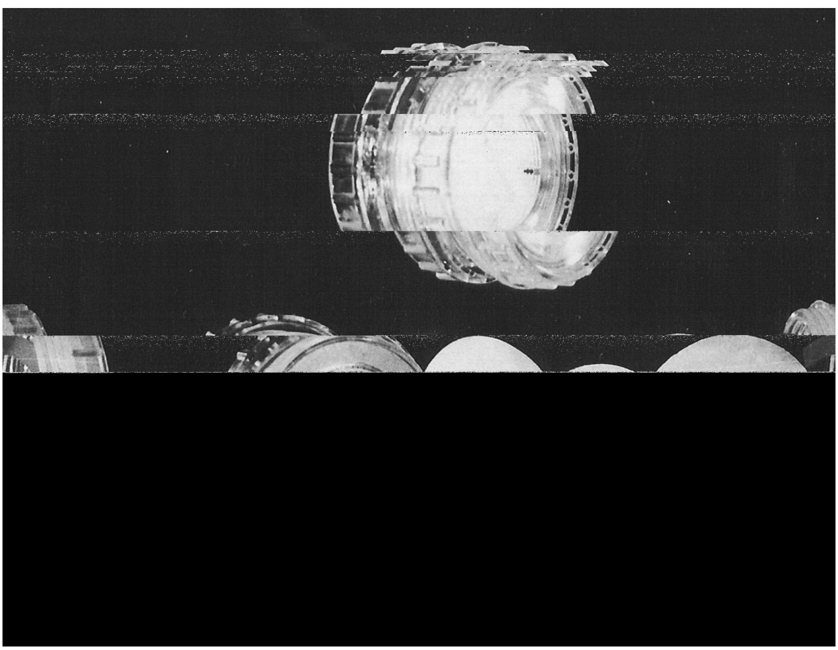

Fig. 9.2. Type 2 test bodies deemed to be used for the exposure of viruses in validation procedures (virus material is adsorbed onto the membrane between the two membrane filters).

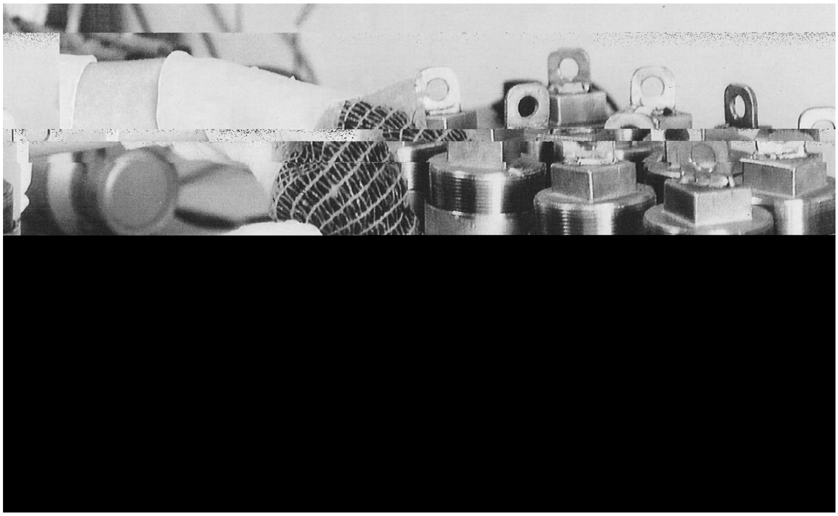

Fig. 9.3. Test bodies deemed to be applied in validating of composting reactors with different test organisms mixed with substrate.

The choice of test organisms and the techniques applied depend on the origin of the raw materials and the intended utilization of the product (Böhm, 2004). Several test organisms other than *Salmonella senftenberg, W775* (H_2S negative) are in discussion for different purposes and treatment processes, especially in the Scandinavian countries (Christensen et al., 2001). Some of the most important are:

- *Enterococci faecalis*;
- *Escherichia coli*;
- *Campylobacter*;
- *ECBO virus*;
- *Bovine Parvovirus (BPV)*;
- *Coliphages*; and
- *Ascaris suum*.

Enterococci, better known as *Enterococcus faecalis*, may be especially used for validating thermal treatment, since their heat resistance covers most pathogens in this epidemiological context, providing a high safety margin. The application of *Enterococci* for the general purpose of validation of composting processes, on the other hand, has some disadvantages. First, the quantitative enrichment is less effective than in *Salmonella* if contaminant flora shall be excluded. If the carriers are exposed to a composting process, it may happen that the test material is contaminated with indigenous *Enterococci*. In this case, contamination from the substrate cannot be detected in an easy and reliable manner. Finally, it must be kept in mind that *Enterococci* are more chemo- and thermo-resistant than most relevant pathogens in this field, but do not have any epidemiological importance in this context. This means that the application of test organisms must be strictly related to the process to be judged. If only a process of thermal inactivation like a pasteurization unit is to be validated, *Enterococcus faecalis* is the proper organism. If a thermophilic aerobic or anaerobic process shall be validated, it is more realistic to use the above characterized strain of *Salmonella senftenberg* because *Enterococci* would be too hard a criterion for this purpose since their chemo-resistance is different from the relevant mostly Gram-negative pathogens. For practical considerations, the proposed serovar *Salmonella senftenberg* has the advantage that it is rarely present in the raw material and can be easily identified by a natural marker (H_2S negative) from accidental contaminants. *Escherichia coli* and *Campylobacter jejuni* are not as resistant as the above-mentioned *Salmonella* strain; the same applies to ECBO virus. It could be demonstrated that if dealing with a moderate epidemiological risk, e.g., given in composting source-separated biowastes, *Salmonella senftenberg W775* will cover the most relevant viral pathogens causing notifiable diseases in farm animals and which may be present in low concentrations in the raw material. The time necessary for the inactivation of viral pathogens is generally shorter or in the same range as for inactivating 5 log of *Salmonella senftenberg W775*, H_2S negative as has been demonstrated by Braumiller et al. (2000), as well as Moss and Haas (2000). The latter results are summarized in Table 9.10; the results demonstrate the range of time necessary for reducing the infectivity of the tested viral pathogens for 3–4 log 10 steps.

Since recently it was stated by Emmoth et al. (2004) that heating of animal by-products to 70°C for 60 min is not enough for the inactivation of Circoviruses and it had been demonstrated by Böhm et al. (2002) that the plant pathogenic tobacco mosaic virus withstands such treatment without any significant reduction, the consequence for the future will be to validate any kind of treatment if such viruses may be present in involved materials. It is obvious that the recommendations of regulation EC 1774 (2002) will not even lead to a safe inactivation of vegetative bacteria, as can be seen from Fig. 9.4, given the temperature curve measured in the reactor in relation to the survival of *Enterococci* in the substrate and on exposed carriers (Braumiller et al., 2000). As a consequence, concerning composting of animal by-products and catering wastes, a validation with a test organism covering the higher epidemiological risk is necessary. This means that there is a clear indication for using Bovine Parvovirus in such a situation.

Table 9.10. Inactivation times during semi-technical in-vessel composting for selected viral pathogens in a temperature range between 25 and 65°C (Moss and Haas, 2000)

Pathogen	Initial titer[a]	Detection level[a]	Inactivation time
Swine Vesicular Disease Virus	6–8 log 10 KID_{50}	1–4 log KID_{50}	27–72 h[b]
Foot and Mouth Disease Virus	6–7 log 10 PFU	1–2 log 10 PFU	12–144 h
Classical Swine Fever Virus	5–6 log 10 KID_{50}	1 log 10 KID_{50}	12–144 h
Aujeszky Disease Virus	5–6 log 10 KID_{50}	1 log 10 KID_{50}	20–192 h
African Swine Fever Virus	5–6 log 10 KID_{50}	1–2 log 10 KID_{50}	27–168 h[b]

[a]Reduced to full log steps.
[b]Insufficient inactivation within 27 h if not at least 55°C had been reached.

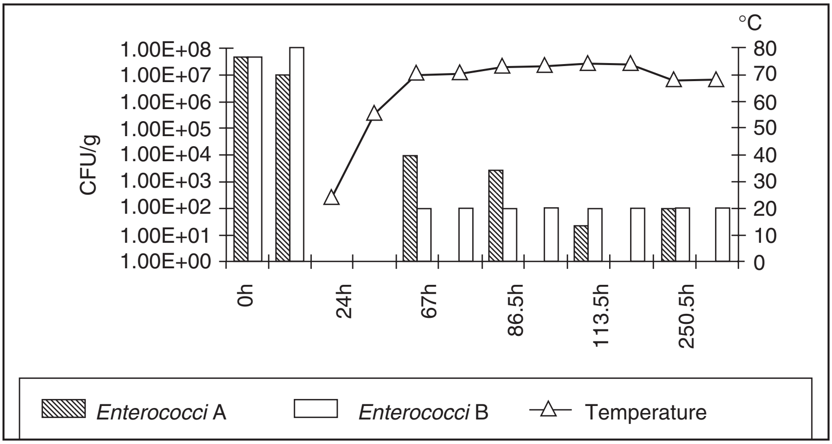

Fig. 9.4. Inactivation of *Enterococci* in two different test devices during in-vessel composting. A — Type 3 Carriers; B — Type 2 Carriers

It must be kept in mind that validation with a representative test-organism alone ("direct process validation") has, as every solitary procedure, advantages and disadvantages, which can be summarized as follows:

Advantages

- Quickly provides the basic information regarding whether or not a technical process leads to a safe product.
- Validates that the producer or technical equipment is protecting the processing plant.
- Helps to define the technical requirement for a safe process.
- Gives a reproducible result which allows comparison of data.

Disadvantages

- High cost and labor intensive.
- It is a rare event.
- Cannot detect accidental disturbances of the process.

The validation with pathogens and seeds may be regarded as an "indirect process validation." However, this validation must be accompanied by continuous recording of measurable process data like temperature, pH, humidity, etc. in order to detect deviations and disturbances of the process over the entire year, which may result in an insufficient bactericidal effect. The advantages and disadvantages of an indirect process control applied alone are as follows:

Advantages

- Easy to achieve and quick.
- Continuous control is possible.
- No special expertise is necessary and laboratory work is limited.

Disadvantages

- Limited representativity for the entire process (gradient formation in the material).
- Influences due to inhomogeneity of the material could not be detected.
- Valuable only in combination with the direct process validation.

The system of process validation and control has to be completed by continuous monitoring of the final product, at least twice a year. As mentioned above, the investigation of the final product to detect every pathogen that may be present in the material is extremely difficult. Therefore, representative indicator organisms have to be determined from the point of view of human and animal health, and if necessary for the purpose of safe plant breeding and production. Several strategies have been followed in different countries and in several normative approaches; an example is given in Table 9.9. Since the philosophies followed in this connection are very different, indicators will be discussed in another section. Additionally, sample collection, storage, and transport have to take into account the special properties and behavior of the biological agents; simple adaptation of methods and recommendations common for chemical analysis is misleading. The advantages and disadvantages of end product monitoring alone as a single strategy to achieve hygienic safety in composting are as follows:

Advantages

- Easy to achieve; limited expertise is necessary.
- Easy to administer and supervise.
- Inexpensive and independent from the site of production.

Disadvantages

- Representative sampling of bulky material is difficult.
- Occurrence of pathogens and indicators depends on the type, origin, and microbiological properties of the raw material.
- Microbiological analysis is influenced by the different products (e.g., growth inhibition).
- Valuable only if applied on products from validated and supervised processes.

Restriction in the use of compost resulting from insufficient treatment should prevent introduction of undesired chemical residuals by contaminated crops into the food chain or direct transmission of pathogens to susceptible animals via feedstuff. This had been practiced in the past, especially with sewage sludge. Such a strategy alone does not prevent the environmental risks or introduction of pathogens into vector populations, which will lead to indirect transmission cycles.

Several authors have given examples of how birds can become carriers of *Salmonella* (Hellmann, 1977). One of the sources of infection in seagulls has been found to be sewage treatment plants. Other ways of introduction of a certain lysotype of *Salmonella enteritidis* can be demonstrated by the work conducted by Köhler (1993). Köhler identified the waste delivered from West Berlin to a waste disposal site in the former German Democratic Republic and followed the introduction of this pathogen via birds into chicken populations and finally to humans via products containing eggs. Williams et al. (1977), as well as several other authors such as Coulson et al. (1983) and Mayr (1983), described the importance of vectors in the transmission of *Salmonella* to farm animals and humans. Foster and Spector (1995) described specific molecular mechanisms responsible for the ability of *Salmonella* to survive the environmental stress, which is underlining the importance of this group of pathogens.

This means that even if the fertilizers containing pathogens are immediately ploughed into the soil, they may generate carriers by attraction of certain species (seagulls) or prolonged survival in subsurface soil layers. Thus, restrictions in use are a tool with limited effect from the point of view of epidemiology and should be avoided if possible and feasible. Moreover, concerning plant pathogens and seeds, this strategy is ineffective if the products are to be used in agriculture.

9.7. Regrowth Prevention

Regrowth mainly concerns bacterial pathogens, since viruses except bacteriophages cannot propagate due to the lack of host cells in this environment. Several bacterial pathogens like *Salmonella* can grow at temperatures between 4 and 44°C, as long as enough nutrients and moisture are available. This is not only a matter of material properties and storing conditions, but also of proper management of tools and equipment from a hygienic point of view. A strict division of the technical equipment involved must be provided. One type of equipment should be used only with the raw material and another one should be used only with the finished product (black and white principle). Otherwise, a reliable disinfection measure has to be carried out in between if the strict division cannot be assured. There is sufficient evidence from practical experiments that moist and contaminated fresh material adhering to the equipment will lead to recontamination of the product even if the material seems to be stable and dry. Since most bacteria will not propagate in a dry product even if nutrients are present, the product must be stored under dry conditions. The vapor pressure within the product should be in balance with a relative humidity of the air of at least 90%. Xerophilic fungi may still grow if this balance is above a relative humidity of about 65%. In general, most bacteria and fungi do not grow in the material if the water activity (a_w value) is below 0.80. In order to achieve product safety by preventing regrowth, recontamination by living vectors like birds and rodents should be avoided by taking adequate measures.

9.8. Indicators

If a product must be evaluated in the framework of microbiological quality control, it is very difficult to investigate it for presence or absence of all pathogens that could be attended. Since financial and technical limitations are given, one of the most practical means to come to a conclusion concerning hygienic safety of a product with a reasonable effort and limited costs is the application of a suitable indicator concept in combination with process validation and indirect process supervision. The indicator concept is only effective if the raw materials are relatively homogenous in their microbiological properties or certain (mostly fecal) contaminants can either be totally excluded in the raw material or have to be always present. This, in general, is not the case here, neither for biowastes nor for industrial wastes or organic sludges. This means that any indicator concept within this framework must be a compromise and the selection of a microbial indicator is extremely difficult and mainly influenced by underlying philosophies. Nevertheless, those indicator organisms must fulfill several requirements:

- they have to be present with a high probability in the raw materials involved,
- the transmission via products must be a factor in epidemiology,
- if a biotechnological process is used, the indicator should not be involved in the process itself,
- the indicator should not be an organism that is generally present in soil and soil-related materials, and
- the method for isolation and identification must be simple, definitive, and reliable if applied to a substrate with a complex microbiological matrix such as compost, sludge, or related materials.

With respect to public health and veterinary requirements, several indicators and parameters are currently under discussion:

- *Salmonella*;
- *Enterococci* (*Streptococci* of group E);
- *Staphylococcus aureus*;
- *Enterobacteriaceae*;
- *Escherichia coli*;
- *Campylobacter*;
- *Yersinia* sp.;
- *Listeria* sp.;
- *Clostridium perfringens*;
- sulfite-reducing *Clostridia*;
- enteroviruses;
- rotavirus;
- eggs of nematodes; and
- larvae of nematodes.

Since compost and related products are coming out of a microbial degradation process and the knowledge about the microbiological ecology of such materials is very limited, one must be careful to use isolation and identification techniques common in clinical microbiology without careful validation in combination with the involved sample materials. The variety of species to be present in environment, samples, and materials resulting from aerobic or anaerobic biological treatment far exceeds the limited number of species to be taken into account in excreta, as well as in body fluids and the variability of species is high and not yet fully understood. Moreover, microbial parameters that are used in the field of water hygiene and food inspection are not applicable to substrates like manure, stabilized sludge, or compost because most of those indicators belong to the indigenous flora of agricultural soils (Böhm, 1995). If the limited reliability and applicability of methods used in clinical microbiology and in water inspection for the intended field of use are taken into account, as well as the fact that the exclusion of organisms that generally may be found in normal soils gives no sense for a substrate and fertilizer such as compost or sludge, the following microbial parameters are inappropriate: *Staphylococcus aureus*, *Enterobacteriaceae*, *Clostridium perfringens*, sulphite-reducing *Clostridia*, and *Listeria*. Especially *Enterobacteriaceae*, for which threshold values are given in the EC regulations 1774/2002, are an inappropriate parameter in the evaluation of products after aerobic or anaerobic biotechnological treatment. This is due to the fact that this parameter does not correlate with the presence or inactivation of pathogens as can be observed in Fig. 9.5. The data in Fig. 9.5 show the results of input and output analyses in validated and non-validated composting plants.

One parameter that seems to be very useful and reliable in this connection is the absence or presence of *Salmonella*. *Salmonella* are generally found in fresh biowastes or untreated sewage sludge with a high probability in various concentrations. Since it is known that the probability of identifying a positive sample is basically related to the amount of material investigated, a compromise between feasibility and reliability has to be found. It is proposed to investigate 50 or 100 g (2 × 50 g) of compost for the presence or absence of *Salmonella* with the method described in principle in the German Biowaste Ordinance using a pre-enrichment in buffered peptone water and an enrichment step (Rappaport et al., 1956; Edel and Kampelmacher, 1969; Vassiliadis, 1983), or other validated method that may be developed within the framework of CEN TC 308.

Some other parameters are still in discussion with respect to sewage sludge treatment and composting in the framework of EU directives. *Enterococci*, for example, cannot be used as an indicator in the examination of compost and compost-related products, but they are valuable for the thermophilic anaerobic treatment in biogas plants and for pure thermal treatment (Bendixen, 1999).

For *E. coli*, *Campylobacter*, and *Yersinia*, besides the lack of reliable re-isolation techniques, it must be stated that their thermo-resistance and, with minor exceptions, chemo-resistance are lower than those of *Salmonella*. This means that it will make no

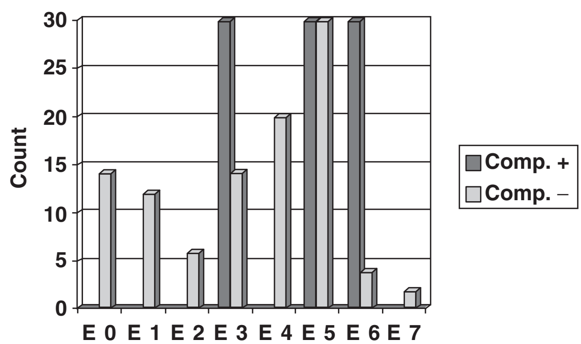

Fig. 9.5. Distribution of enterobacterial count in composts containing *Salmonella* (Comp. +) and in composts coming out of validated processes being tested negative for S*almonella* (Comp. −)

sense if they are used as additional microbial parameters for describing a hygienically safe product.

Enteroviruses are generally present in sludge of fecal origin but not regularly in sludges coming from other sources. In principle, enteroviruses may be used as additional indicators but the re-isolation procedures, as for all viruses from environmental samples, are labor intensive and costly. Their resistance in the involved treatment processes is not higher than that of *Salmonella*; this means that the additional information resulting from using these indicator organisms is also low. The same applies for rotavirus, even it is of special environmental importance, according to Metzler et al. (1996) and Pesaro et al. (1999). Recent investigations have shown that coliphages do not correlate high with gut-related pathogens or other comparable fecal indicators even in substrates of fecal origin, as can be seen from Fig. 9.6 (Samhan, 2005).

The question of whether or not nematodes or nematode eggs are useful indicators in this connection is not easy to answer. With respect to nematodes pathogenic to men and/or animals, experience shows that even eggs of *Ascaris suum* are less thermo-resistant than *Salmonella*, but behave differently in chemical treatment. This means that if *Salmonella* does not survive the composting process, *Ascaris* eggs and all other nematodes eggs would not either. This does not apply for treatment with slaked lime or long-term storage, especially in connection with organic sludges. This means that *Ascaris* eggs will not be a necessary indicator in all processes in which the thermal effect is the predominant one, but they will give valuable additional information if used in the monitoring of all other treatment processes.

Finally, the problem of indicator organisms from the phytohygienic point of view must be discussed. No virus, fungus, or bacterium pathogenic to plants has been found thus far that is of comparable importance as *Salmonellae* are for the purpose mentioned above. The only indicator that is widely distributed in biological wastes from households is tomato seeds. Even knowing that this indicator will not totally cover all requirements, it seems to be reasonable and feasible to define the term “phytohygienic safety” of the

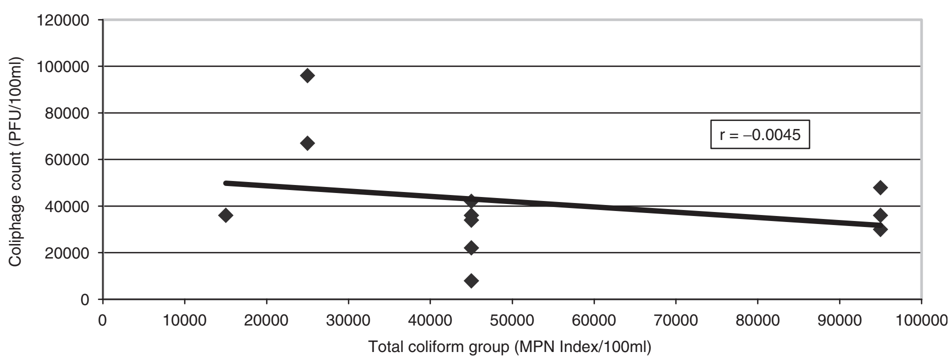

Fig. 9.6. Correlation between the parameters “coliform bacteria” and “coliphages” in sewage samples (Samhan, 2005).

product as follows: The final product should not contain more than two seeds capable to germinate and/or reproduce parts of plants in 1 L. A suitable test method is described by Bundesgütegemeinschaft Kompost (1994).

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Chapter 10

Suppression of Soil-Borne Phytopathogens by Compost

J.D. van Elsas and J. Postma

10.1. Introduction

Compost is used in agriculture and horticulture as a fertilizer or to improve the physical structure of soil, including potting soil mixtures. In addition, compost-amended soil has been found to show enhanced suppression of plant diseases caused by soil-borne nematodes, fungi and bacteria, in various cropping systems (Hoitink and Fahy, 1986; Ringer, 1998; Schönfeld et al., 2002). Conversely, an increase of disease incidence due to a compost application has also been demonstrated (Tuitert et al., 1998; Hoitink and Boehm, 1999). The fact that compost application can affect the suppression of disease in cropping systems in positive, neutral, or even negative ways still makes the application of compost complicated as a robust universal strategy to curb plant disease.

Our knowledge of the mechanisms that influence the interactions between the beneficial microorganisms, the pathogens, and the crop in relation to the organic matter in the compost, as well as in the soil, is still not complete. Compost can influence those interactions in several ways. The attack by soil-borne plant pathogens can be inhibited (or enhanced) by the use of compost: (1) directly through its chemical and physical properties, (2) through the microflora present in the compost, (3) by stimulating the (antagonistic) microflora in soil and around plant roots, and (4) by inducing stronger and healthier plants. This chapter focuses on the interactions between the microflora (in compost and soil) and disease development by soil-borne pathogens (items 2 and 3 above). The net results of these poorly understood interactions are the ultimate determinants of the functionality of compost as a disease-suppressive substrate. Therefore, predictions on the beneficial effect of compost products in cropping systems are still unreliable.

Several reasons for the variable and sometimes inconsistent results of compost application on disease suppression can be given. First, there are many types of compost. Compost can inherently differ in composition with respect to the quality and quantity of organic materials, nitrogen content, carbon-to-nitrogen ratio, pH, and degree of maturity. Second, the method, dose, and time of compost application and environmental conditions are important for its ultimate effect in the field. The obvious aim of compost use is to achieve an optimal reduction of pathogen threat to crop plants, but the application of organic material at the "wrong" time can even stimulate the activity of pathogens present in the soil. Such a "wrong" timing can be the addition of compost just before planting a crop (Hoitink and Boehm, 1999; Postma, unpublished data).

It is thus clear that we currently lack a good understanding of the requirements with respect to compost quality; the mode, dose, and timing of compost addition; and the status of the recipient soil. This lack of knowledge prevents the design of robust compost application strategies for practical purposes. More knowledge on the production, quality, and disease suppressiveness of compost and its compatible application in agricultural systems with respect to soil, crop, pathogen ecology, and compost microbiology is clearly needed to better predict the beneficial effects of compost applications. Fig. 10.1 depicts the key factors and strategies that affect the functionality of compost added to soil with respect to suppression of plant diseases.

10.2. Production of Disease-Suppressive Compost

10.2.1. History of Disease-Suppressive Compost

The first well-documented results with respect to the production and use of disease-suppressive compost were published in the 1970s (Malek and Cartner, 1975; Hoitink et al., 1977). Composted hardwood bark was produced, which was used as a substitute

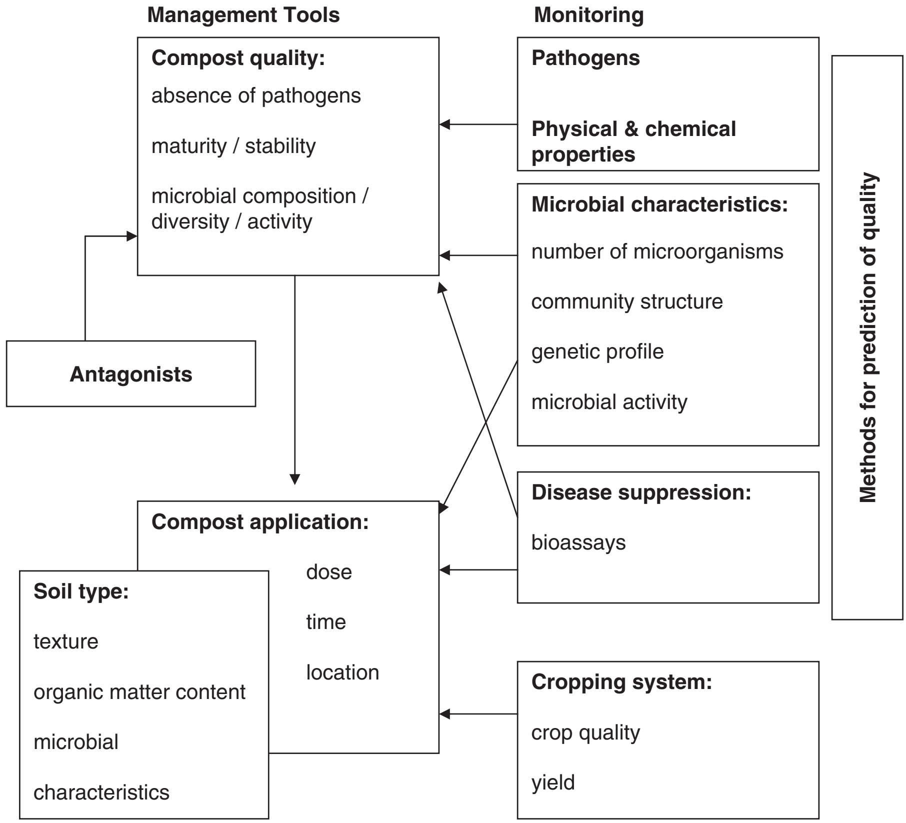

Fig. 10.1. Flowchart of compost quality and factors that influence the success of application, and the characteristics that can be monitored to predict or evaluate the effect.

for peat in container systems. *Phytophthora cinnamomi* (Hoitink et al., 1977) and plant-parasitic nematodes such as *Meloidogyne*, *Pratylenchus*, and *Trichodorus* species (Malek and Cartner, 1975) were inhibited by the addition of compost to the container medium. The mode for action of this compost type and the intricacies of its use were, however, never thoroughly investigated. As a result of these initially promising results, bark compost is now being largely applied in container systems for growing different types of shrubs and young trees in the United States.

These initial findings were followed by a cascade of research data from other parts of the world in the search for other types of suppressive compost (Lumsden et al., 1983; Hadar and Mandelbaum, 1986; Craft and Nelson, 1996; Ringer, 1998; Tuitert et al., 1998; Ryckeboer, 2001). Different types of organic waste have been composted and analyzed for disease-suppressive properties. Waste materials such as organic household waste (vegetable, fruit, and garden waste) are inexpensive products in several parts of the world. These materials could be sold profitably if they could stimulate disease suppression.

Recent research data show that compost prepared from such waste materials can be disease-suppressive (Tuitert et al., 1998; Ryckeboer, 2001; Blok et al., 2002; Postma et al., 2003), but the data often lacked consistency. Several compost producers are known to aim for high-quality compost, targeting specific crop production systems and a high suppressiveness for diseases ("tailored" compost). Mixtures of different types of materials (manure, lignin-containing materials, other green wastes) are thus used for the preparation of compost, aiming for a "good" (beneficial) product in the view of the grower. This allows the valorization of otherwise superfluous waste material.

As compost can be variable in terms of composition and chemical, physical, and biological parameters, there is a need to design a more consistent or reliable way of composting. Thus, the Controlled Microbial Composting (CMC) method is a composting procedure that includes inoculation with a mixture of microbes present in a CMC compost starter (Diver, 2002). In addition, CMC compost is carefully and frequently turned over and takes only 6–8 weeks to prepare (Diver, 2002).

The quality of the compost that is claimed to suppress plant diseases is, in addition to physical and chemical analyses, usually determined by microbiological methods and *in vitro* disease inhibition tests. Such quality controls are important for compost producers, as well as for compost users, but may not relate to disease suppression in practice. Since there is still no scientifically accepted disease suppressiveness measurement, the analysis of the suppressive characteristics of compost is still prone to development. The ultimate aim of this should be the design of a robust methodology that relates to the suppressive status of compost in practice.

10.2.2. In Search of Parameters that Relate to Compost Disease Suppressiveness

In spite of the many efforts to find determinants (indicators) of disease suppressiveness, there is still a general lack of understanding of what determines the disease-suppressive status of compost. However, it is very likely that disease suppressiveness of compost can be caused by a complex interplay of a range of abiotic (pH, C/N, organic matter quality, etc.) and biotic (predators, antagonists, and competitors for nutrients) factors. Prediction of suppressiveness of compost is complex, not only due to the complexity of the compost itself, but also due to the different soil-borne pathogens (fungi, nematodes, bacteria) that should be suppressed. It is obvious that an ideal suppressive compost should suppress a broad range of pathogens, but different pathogens will probably react differently in relation to disease-suppressive compost.

Although general indicators for suppression are not available, several promising examples of disease suppression have been described for specific situations and diseases. This clearly indicates a relationship between disease suppression and specific chemical, physical, and biological characteristics in the compost. In the following paragraphs, we will discuss such characteristics of compost that may relate to disease suppression, and concomitant parameters that are thought to predict compost functionality.

10.2.3. Composting Procedure and Compost Maturity

The maturity and stability of compost are important for the degree of disease suppressiveness of soil that can be achieved. In a stable compost, easily degradable carbon sources have been used by the microflora present, leading to a stable microbiological system. Extremely stable compost is expected to have little effect on soil suppressiveness. In fresh compost, nutrient sources have not been depleted. When such immature (fresh) compost is applied to soil, plant diseases can be curbed, but can also be stimulated. According to relatively recent data, it is the partially stabilized (matured) and fully colonized compost that will have optimal disease-suppressive characteristics (Hoitink and Boehm, 1999). On the other hand, Tuitert et al. (1998) showed that fresh as well as long-term, matured (5–7 months of curing) compost added to potting soil clearly inhibited the outgrowth and disease development by *Rhizoctonia solani*, whereas short-matured compost (1-month curing) stimulated pathogen growth. A consistent and unambiguous measure for the maturity or quality of compost, which relates to disease suppression, has not been put in place yet.

Compost maturity can be estimated using different techniques, of which the self-heating test is the most simple and still valuable. To obtain more detailed information about chemical properties of compost that relate to its maturity, it has been suggested to use cross-polarized magic angle spinning ^{13}C-nuclear magnetic resonance (CPMAS ^{13}C-NMR) technique to characterize compost (Boehm et al., 1997; Hoitink and Boehm, 1999). With this method, the content of carbohydrates within the fine (105–250 μm diameter) compost particles can be analyzed. This gives an indication of compost quality as it relates to disease suppression. However, the method still needs to be validated by experimentation, including sufficient samples representing various ways of producing compost of different qualities and maturity.

10.2.4. Microbial Succession during the Composting Process

The microbial succession during the composting process can be separated into different phases, as guided by the temperature regime. During the first mesophilic phase, temperatures increase rapidly to 40–60°C, when sugars and other easily biodegradable substances are utilized (Hoitink and Boehm, 1999). During the second thermophilic phase, temperatures of 40–70°C prevail and cellulosic and other less well biodegradable substances are broken down. In the third phase (curing or maturation phase), temperatures decline from 40°C to that of the environment (Hoitink and Boehm, 1999). When temperatures drop, the total bacterial numbers decrease, but their taxonomic and metabolic diversities increase. This microbial succession during the composting process is described by Ryckeboer (2001). An overview of the presence of 123 species of prokaryotes and 251 fungal species during the mesophilic and thermophilic phases in relation to different source materials of compost is provided. The shift in the microbial composition during the maturation of several compost types was also detectable with the molecular microbial community fingerprinting technique, polymerase chain reaction – denaturing gradient gel electrophoresis (PCR-DGGE) (Blok et al., 2002) and with phospholipid fatty acid (PFLA) analysis (Boulter et al., 2002).

10.2.5. Correlation of Disease Suppressiveness of Compost with Microbial Characteristics

Attempts have been made to correlate the degree of disease suppressiveness of compost by measuring the microbial activities in the compost product itself. The suppressiveness against *Pythium graminicola* was found to be correlated with general microbial activity, as measured by fluorescein diacetate (FDA) hydrolysis (Craft and Nelson, 1996). Results of nine different composts added to sand in a bioassay with creeping bentgrass showed that increasing levels of *Pythium* damping-off suppression correlated with higher levels of FDA hydrolysis in the compost.

The complexity of correlating disease suppression of compost with microbial characteristics was clearly shown by Blok et al. (2002). Nine types of compost of different maturation stage were tested for the suppression of three pathogens. For *Phytophthora cinnamomi*, the level of suppressiveness was largely explained by general microbial activity, measured as basal respiration (i.e., CO_2 production without addition of substrates). Suppressiveness of *R. solani* was largely explained by organic matter quality (i.e., an index indicating the suitability of the organic matter of the soil–compost mix as a food source for the microflora). Furthermore, suppression of *Pythium ultimum* was not explained well by any of the measured values. The three pathogens reacted differently to a variety of compost types.

It is likely that the community structure (numbers, activity, and diversity) of the microflora present in the compost determines the degree of suppression of plant disease. Attempts have been made to index composts for numbers of specific microbial groups that are known to inhibit a wide range of phytopathogens. High numbers of actinomycetes were present in those compost types that showed phytopathogen-suppressive power (Craft and Nelson, 1996). Also, Tuitert et al. (1998) showed a relation between disease suppressiveness of compost and numbers of actinomycetes. In long-matured compost, suppressiveness of *R. solani* was associated with high population densities of cellulolytic and oligotrophic actinomycetes. The ratio of actinomycetes to total bacteria in mature, disease-suppressive compost was 200-fold higher than in disease-conducive compost.

Another microbial group that was studied in relation to compost suppressiveness was the genus *Trichoderma*. Compost prepared from lignocellulosic materials such as tree bark with suppressive properties towards *Rhizoctonia* is predominantly colonized by *Trichoderma* spp. (Hoitink and Boehm, 1999).

It is likely that, in addition to actinomycetes and *Trichoderma* spp., other microorganisms also correlate with suppressiveness of compost. Boulter et al. (2002) found that a high percentage of the bacterial isolates from compost exhibited antagonistic activity *in vitro* against different fungal pathogens (19–52% of isolates inhibited several turfgrass pathogens). A range of different bacterial and fungal groups, such as pseudomonads, *Serratia* spp., *Burkholderia* spp., *Bacillus* and *Peanibacillus* spp., and specific (mycoparasitic) fungi, are known to be able to exert antagonism against phytopathogenic bacteria and fungi. Their prevalence and activities in different types of compost are still largely enigmatic and we clearly need more investigation with respect to the actual diversity and activity of these antagonistic bacteria and fungi in compost.

It is a long-standing dogma that microbial diversity is a major factor that, by itself, determines the suppressive nature of compost. However, microbial diversity is a highly complex issue, which is far from being completely understood. The degree of microbial activity within the compost, the interaction with the soil to which the compost is added, and the subsequent contact with the pathogen are all phenomena to be taken into account if the effects of compost microbial activity are to be understood.

10.2.6. Addition of Disease-Suppressive Microorganisms

Spiking of compost with disease-suppressive microorganisms is a method that may enhance the disease-suppressive properties of compost. During the thermophilic phase of the composting process, many organisms are killed. Thereafter, a succession of the indigenous and exotic microflora occurs. Host-specific antagonists are not expected to be present in the early stages after composting. Enrichment of the compost with specific antagonists might therefore increase the reliability of the compost to suppress certain pathogens.

Addition of specific organisms to compost has already been tested and commercialized (Segall, 1995). Potting mixtures containing dark peat, light peat, or composted pine bark were not always suppressive against *Rhizoctonia*. The inoculation of these potting mixes with *Trichoderma hamatum* 382 and *Chryseobacterium gleum* 299 (synonym, *Flavobacterium balustinum* 299) improved the disease suppressiveness significantly (Krause et al., 2001). Similar results were obtained by Ryckeboer (2001), who introduced *T. hamatum* 382 and *C. gleum* 299 to vegetable, fruit, and garden waste compost and to green waste compost, where they were used as an amendment in potting soil to improve suppressiveness towards *Pythium ultimum* and *R. solani*.

Another example of improving compost suppressiveness by adding microorganisms is the introduction of potential fungal antagonists (*Acremonium, Chaetomium, Gliocladium, Trichoderma*, and *Zygorrhynus* sp.) into compost (Sivapalan et al., 1994). Also, the addition of highly effective cellulose decomposers (*Trichoderma viride* NRC6 or *Streptomyces aureofaciens* NRC22) in the composting process of agricultural wastes, or the addition of arbuscular mycorrhizal fungi to compost had positive effects (Badr El-Din et al., 2000). These organisms probably made nutrients more available for plants and suppressed the development of soil-borne pathogens (Badr El-Din et al., 2000).

The addition of the fungal antagonists *Verticillium biguttatum* and a non-pathogenic isolate of *Fusarium oxysporum* to different types of compost was recently evaluated (Postma et al., 2003). The data in Fig. 10.2 show that *V. biguttatum* had a positive effect on the suppressiveness of the compost against *R. solani.* The non-pathogenic isolate was antagonistic

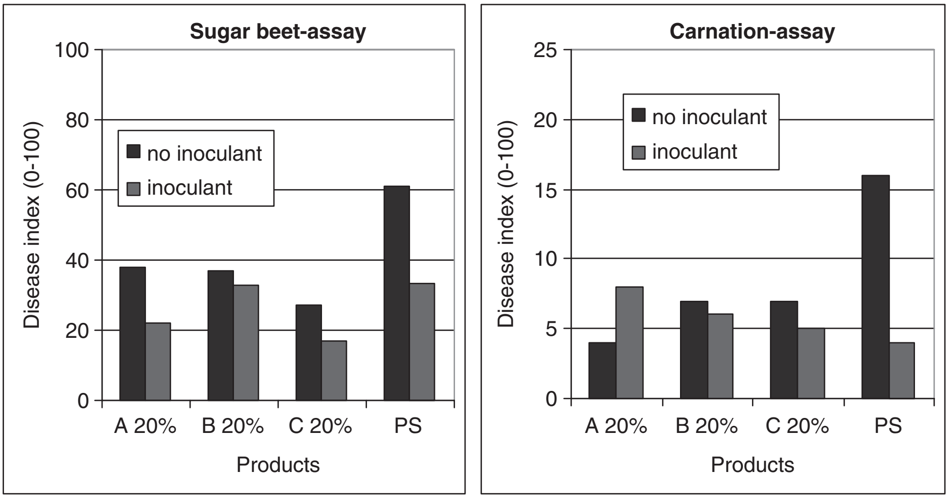

Fig. 10.2. Disease expression of *Rhizoctonia solani* in sugar beet and *Fusarium oxysporum* in car-

phytotoxicity for the crop and the soil structure. Another application with high dosages of compost is the use of compost in the form of mulch, where up to 100 tons/ha has been applied. It is clear that such a high dosage of compost can have great impact on the soil microflora and on its suppressiveness. As a consequence, many studies about the effect of compost on disease suppressiveness are dealing with container systems with high compost dosages, showing disease suppressiveness for many pathogens such as *Pythium*, *Phytophthora*, *Fusarium*, *Rhizoctonia*, and nematodes (Malek and Cartner, 1975; Hoitink et al., 1977; Hadar and Mandelbaum, 1986; Hoitink and Fahy, 1986; Blok et al., 2002; Postma et al., 2003). A recent extensive research was executed by various European research groups evaluating 18 composts in seven pathosystems (*Verticillium dahliae* – eggplant, *Rhizoctonia solani* – cauliflower, *R. solani* – pine, *Phytophthora nicotianae* – tomato, *P. cinnamomi* – lupin, *Cylindrocladium spatiphylli* – spatiphyllum, *Fusarium oxysporum* – flax) (Termorshuizen et al., 2006). Applying 20% of compost into potting soil or sand, 54% of the tested combinations were significantly more disease suppressive, 3% showed significant enhancement of the disease, and 43% of the tested combinations did not result in significant differences compared to the control without compost. The mean disease suppressiveness per compost ranged from 14 to 61% (Termorshuizen et al., 2006). Thus, generally speaking, a dosage of 20% compost has a positive effect on suppressiveness of potting soil or sand. However, none of the compost types could improve the suppressiveness of the potting soil for all tested pathosystems.

10.3.2. Application in Field Soils

The application of compost to field soils on large areas is limited as a result of physical constraints. In the Netherlands, regulations limit the application of compost to 12 tons/ha of field soil over 2 years, which is less than 1% w/w (regulation based on heavy-metal content). One can question if such a low dosage can still have an impact on the microflora, as well as on disease suppression. Applying 1% w/w compost [containing 10^8 to 2×10^9 colony-forming units (CFUs) of aerobic bacteria per gram dry matter] to an agricultural soil containing between 10^7 and 10^8 CFU aerobic bacteria per gram obviously will not result in a substantial increase in total number of microorganisms. However, there are two effects that can make the compost application effective. First, the composition of the microflora in compost is most likely quite different from that of soil. Second, the soil will be enriched with a variety of nutrients that become available to the indigenous microflora. The result will often be a shift in the soil microflora, which can result in an enhanced disease-suppressive activity. Such shifts can be measured with molecular techniques such as PCR-DGGE (Postma and Kok, 2003; Schönfeld et al., 2002) or terminal restriction fragment length polymorphism (T-RFLP) (Tiquia et al., 2002). Also, methods at the functional level [community-level physiological profiling (CLPP) with BIOLOG plates] can be applied to study shifts in the soil microflora (Garland and Mills, 1991; Postma and Kok, 2003).

In spite of the application of a low dosage of compost (1% w/w), disease suppression has been shown for *Rhizoctonia*, *Pythium*, and some nematodes (e.g., *Meloidogyne*)

(Postma and Kok, unpublished data; van Os and van Ginkel, 2001). Time and method of application, the type of compost, and the type of soil are probably more important for the disease-suppressive effect at low compost dosages than when high dosages of compost can be applied. In specific situations, i.e., when soil has been partly sterilized by fumigation, solarization, or inundation (flooding during 6 weeks), the application of compost has great potential to quickly enrich the soil microflora with antagonistic organisms (van Os and van Ginkel, 2001; Schönfeld et al., 2002).

10.3.3. Correlation between Compost-Amended Soil Microflora and Disease Suppression

The correlation between disease suppression and pure compost parameters was discussed in paragraph 10.2.5. However, the interaction with the soil to which the compost was added can not be neglected. Results of Termorshuizen et al. (2006) confirmed this statement: parameters based on compost/potting soil mixes showed a higher correlation with disease suppression in different pathosystems than the pure compost parameters. Therefore, it is advised to study the microbial characteristics of the compost-amended soil in relation to its disease suppression.

Different microbial characteristics have been analyzed in relation to disease suppressiveness of different soil types or treatments (Alabouvette et al., 1985; Oyarzun, 1994; van Bruggen and Semenov, 2000; van Os and van Ginkel, 2001). Although microbial activity (measured by dehydrogenase activity, FDA hydrolysis, or respiration) and biomass have been correlated with disease suppression (nutrient sink in suppressive soil), these community-level characteristics could not fully explain the level of disease suppressiveness. Van Os and van Ginkel (2001) showed that the growth rate of a pathogenic *Pythium* species through differently treated soils correlated negatively with dehydrogenase activity, microbial biomass, and $^{14}CO_2$ respiration of the soil. A lower growth rate of the fungus through the soil, however, was not always correlated with a lower disease incidence level in the crop.

For efficient disease suppression, a range of different properties of the microflora are thought to be important. A high microbial diversity, as well as the presence of specific suppressive microorganism(s), might be necessary. Several studies have shown a correlation between the presence of actinomycetes and suppression of fungal pathogens (e.g., *Pythium* and *Rhizoctonia*) in soil or compost (Oyarzun, 1994; Workneh and van Bruggen, 1994; Craft and Nelson, 1996; Tuitert et al., 1998). Actinomycetes are key organisms in the decomposition of various organic substances and they are important producers of antibiotics, vitamins, and many enzymes. Stimulation of actinomycetes after compost application as an explanation of increased soil suppressiveness is therefore an interesting hypothesis for further studies. Actinomycetes are one example of a microbial group that influences disease suppression.

Other organisms responsible for disease suppression, in particular those in the nonculturable fractions of soil microorganisms, can be detected with molecular techniques such as PCR-DGGE (Muyzer et al., 1993; Postma and Kok, 2002; Schönfield et al., 2002).

The suppressiveness of soil to *Ralstonia solanacearum*, the causative agent of brownrot in potato, was enhanced by the addition of organic household waste compost (Schönfeld et al., 2002). Concomitantly, shifts in the microbial populations were found. Specifically, the β-proteobacterial communities changed, with enhanced dominance of *Variovorax* and *Aquaspirillum* spp. The addition of spent mushroom compost or stable green compost to a sandy soil (at 1% w/w) resulted in a shift in the dominant bacterial as well as fungal species, as measured with PCR-DGGE (Postma, unpublished data). Blok et al. (2002) studied the banding patterns of the dominant fungal and bacterial populations for nine types of compost (20% application in potting soil) with PCR-DGGE. A relationship between the banding patterns and disease suppression was not detected. Recently, bacterial populations in rhizosphere samples from bare soil and compost-treated soil were compared using T-RFLP (Tiquia et al., 2002). Changes in the microbial rhizosphere communities were detected. Both molecular methods are powerful tools to study the microbial composition; however, to establish their (causal) relationship with disease suppression, more precise data have to be collected.

10.4. Concluding Remarks

In spite of the current large-scale research on disease suppressiveness of compost, there is still insufficient insight into the general principles of disease suppression by compost in relation to its quality. In spite of several promising examples where compost had a disease-suppressive effect, prediction of efficacy of compost application to the field is still premature. A general robust system with a compost being suppressive for all pathogens and under many circumstances is not likely to be realistic. Tailor-made compost for the suppression of certain pathogens in a specific cropping system is probably needed.

The introduction of added microorganisms to compost is promising, i.e., the microbial enrichment of compost. But also in this case, we are still dependent on a great deal of basic developmental work before we can safely state that the technology has been put to work. Mature compost with an established (inoculated) antagonistic microflora is most likely to give robust results.

Up-to-date information on disease suppression by compost can be found on the Internet (e.g., www.uark.edu/; www.agric.gov.ab.ca/). One very important aspect when considering the application of compost is the dose to be used in relation to the maximal allowable dose. In The Netherlands, additions of compost to soils are restricted to low levels per addition. This probably represents levels below those that are consistently effective. In some other countries, allowable doses are much higher. In addition to the quality of compost, the interaction with soil and the soil microflora is also important. The effect of compost will be most pronounced if applied to a sandy soil with low amounts of organic matter or with a poor microflora (e.g., after disinfection treatments). The timing and mode of addition of compost clearly affect its efficacy. For example, if the organic matter within the compost represents an easily degradable compound, it can stimulate phytopathogens instead of antagonizing their action. But the same organic matter source, after a longer time of incubation, will enhance the suppressiveness of soil when added to it.

Much of research in this area depends on trial and error, aiming for practical solutions for healthy crop growth or preparing a good quality of compost. As a consequence, reliable data are not available worldwide, but often are documented in reports and local journals. Databases, which can be used for comparison of many compost types, their physical, chemical, and microbial properties, and disease-suppressive features, are lacking. "Quality of life and management of living resources," are dealing with suppressiveness of compost and will meet this shortcoming.

10.5. Acknowledgments

We thank Jim van Vuurde for critically reading the manuscript. The research described herein was supported by the Dutch Ministry of Agriculture, Nature Food and Quality (DWK programs 342, 352, and 397).

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Chapter 11

Odor Emissions from Composting Plants

W. Bidlingmaier and J. Müsken

11.1. Introduction

The basis for the preparation of this chapter was the data collected for a project conducted to find the relationship between decomposition management and odor emissions from the composting of urban wastes (project TV1). Project TV1 was conducted to prepare calculation sheets for estimating odor emissions from compost plants. The data collected for the project were supplemented by data obtained in the literature.

Odor emissions are one of the main problems in the planning of a composting facility. It is very difficult to design and build a composting process without the release of odorous substances. The main sources of odors are: the raw material (biowaste or green waste), the metabolic products that arise during aerobic degradation, and some of the metabolic products during anaerobic degradation. Another factor governing odor formation is the method of operation of the composting plant.

The knowledge of odor emissions to be expected from each composting process, independent of the raw material, together with the possible avoidance of these emissions, are fundamental preconditions for successful and environmentally friendly composting. It is always a problem to accurately predict potential odor emissions any time a new composting plant is designed.

For the time being, there are no generally accepted instruments available that allow the designer of a composting facility to calculate expected levels of emissions in a simple, quick, and safe manner when planning the site and when defining the measures to be adopted for emissions reduction taking into consideration all legal requirements.

The assessment of odor emissions typically is based on experimental values that have been gathered on comparable composting plants. However, the transfer of the determined quantity of emissions from one plant to another is difficult since the boundary conditions seldom are the same. Boundary conditions such as input quantities, waste composition, the type of composting technology, dwell time, the temperature of the decomposition material, and many other variables should be especially considered to avoid a substantial misinterpretation of the types and levels of emissions.

In this chapter, uniform approaches and basic data for emission values from composting plants are developed. These should be used as the basis for the calculation sheets for "Odor Emissions." The calculation sheets have been developed to provide assistance to authorities, engineering consultants, and designers of composting plants and will be used in a software program.

11.2. Odor Definition, Measurement, and Generation

Odor is the property of a chemical substance or mixture of substances that, depending on the concentration, triggers the sense of smell and thus is able to cause an odor sensation (Winneke, 1994).

11.2.1. Odor Perception and Sensation

Odor is a parameter that cannot be measured physically or chemically. Odor reflects only the property of a certain substance or mixture of substances. Odor perception is a sensory reaction of the olfactory cells that sit on the dome of the nasal cavity as the olfactory epithelium. A human being has about 10–25 million olfactory cells.

Odor perception, like the perception of tastes, arises through a direct reciprocal effect between chemical compounds and the corresponding peripheral receptor system. Odorous substances that are exclusively transported in air are inhaled by breathing into the olfactory system situated in the upper portion of the nasal cavity. On the other hand, flavoring substances dissolved in an aqueous solution stimulate the sensory cells on the tongue.

The perception of odor is generated through the sense of smell. The sense of smell consists of three main components (Müsken and Bidlingmaier, 1994):

- the nose with its stimulus receptors, olfactory nerve, and its neurons,
- a nerve transmission system for the transfer of electrical pulses generated through the odor perception, and
- part of the brain (olfactory bulb, olfactory tract) where the arriving electrical pulses are processed and transformed into an odor sensation.

Compared with the sense of taste, which is limited to the four sensory perceptions (sweet, sour, salty, and bitter) and which can even be realized in a relatively high concentration, the sense of smell can perceive a relatively unlimited number of chemical compounds at very low concentrations. This is probably the reason for the fact that the sense of smell has not been fully researched until now. All theories about odor perception refer to a strictly limited selection of odorous substances and their exact description of the reactions. Considering the multitude of odorous substances that are known to chemistry, this group represents just a small portion.

Human beings perceive odors very differently. Known or rarely arising odors are felt as being pleasant, as opposed to strange and often arising odors, which are felt to be annoying. As shown in Fig. 11.1, the chain starts at the point where odorous substances leave a plant, with the collection of odorous emissions. These substances are diluted through atmospheric transport (transmission) and lead to a situation of immission, which is responsible for the human reaction to odors.

A perceived odor sensation cannot be mentioned before a psychological interpretation of the odor stimulus has been realized. This odor sensitivity varies widely amongst individuals. The interpretation of odor is dependent upon a multitude of personal and cultural influences. Influences such as education, general attitude toward life, and personal

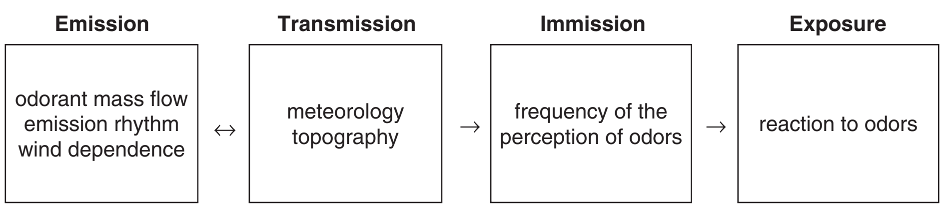

Fig. 11.1. Causality chain for the description of dispersion of odorous substances (Krause and Lung, 1993).

experiences and knowledge can be listed as forming sensations during the creation of reaction patterns to odors.

Another influence can be defined as an attitude of expectation. This means that stimuli that have been perceived with other senses are compared with already stored combinations of stimuli. For example, the term "wastewater" often is connected with the visual impression of putridity and rotten material, which may influence the odor perception. Weller reports that observers of a new, not yet operated wastewater treatment plant mentioned a (negative) impression of the odors (Weller, 1978).

Certain preconditions must be fulfilled before a substance can create an odor impression (Jager and Kuchta, 1993):

Volatility	Under normal conditions, sufficient odorous molecules must be in the air before they enter into the nose and lead to a stimulus.
Water solubility	The olfactory mucous membrane of the nose has a water layer that can be penetrated only if the odorous substance is water soluble.
Fat solubility	The fat layer of the nerve cells can be penetrated only by fat-soluble odorous substances. Organic residues at the odor-active group lead to the fat solubility.
Polarity	The intensity of the polarity is decisive for the perception of the odors. It must be moderately accentuated, as high polar compounds (ionic bonds) are water soluble but not fat soluble and, therefore, are non-odorous.

The following are important for the sensation of odor perception (Anemüller, 1993):

- the frequency and duration of an odor impact,
- the intensity of the odor impact, and
- the quality of the affecting odor.

A certain concentration of molecules leads to a sensation dependent upon the odorous substance and the perceiving individual. However, this alone does not lead to an identification of the odor. The term for this perception threshold is sensation or odor threshold.

As long as odorous substances do not have toxic effects, they are not directly harmful to health. However, since they are perceived through the sense of smell, they leave an impression in the range between being very comfortable to very uncomfortable. This property of odor is known as the hedonic tone.

Odor thresholds may vary from one human being to the other. The perception may change due to disease (e.g., a cold), toxic damage to the olfactory cells (e.g., drugs), or forced impacts to the skull. Permanent impacts of odorous substances on the olfactory cells lead to a deterioration of the sensitivity; these processes are described as adaptation or habituation. Evidence of the influence of age on perception has been found. The odor sensation threshold increases with increasing age, i.e., the sensitivity to odor declines (Anonymous, 1986a). The sensitivity of odorous substances does not increase in the same way as the odorant concentrations (i.e., the number of odor molecules in the air inhaled). The olfactory strength of sensitivity "I" (intensity) is approximately proportional to the logarithmic concentration of the odorant. According to Weber–Fechner (Anonymous, 1992):

$$I = k_{\mathrm{W}} \cdot \log \frac{c_{\mathrm{G,P}}}{c_{\mathrm{G,S}}}$$

with $c_{\mathrm{G,P}} > c_{\mathrm{G,S}}$
$c_{\mathrm{G,S}}$ threshold concentration,
$c_{\mathrm{G,P}}$ odorant concentration,
k_{W} Weber–Fechner coefficient.

The Weber–Fechner coefficient depends on the odorous substance or on the mixture of odorous materials. If an odorous substance A is felt to be more intensive than an odorous substance B with the same odorant concentration, substance A will be assigned a correspondingly higher Weber–Fechner coefficient. On the other hand, two samples of odorous materials with a different Weber–Fechner coefficient have dissimilarly high odorant concentrations if their intensity is felt to be the same.

11.2.2. Fundamentals of Odor Measurement

11.2.2.1. Applied Methods of Odor Measurement

Fundamentally, two different methods of odor measurement can be mentioned: sensory and chemical–physical. The measurement methods are shown in Fig. 11.2.

Chemical–physical methods are divided into the wet-chemical methods and the capillary gas-chromatography method. The wet-chemical method is used to search single substances. This method, however, is of little utility for the measurement of odors in biological waste treatment plants, which emit very complex mixtures of substances.

In the detection of groups composed of individual substances, the capillary gas-chromatography method offers the possibility of separating complex mixtures of substances. The most commonly used detector for this test is the flame ionization detector (FID). This measurement allows a continuous determination of the organic carbon, but even this method does not replace the human nose as an odor detector. According to Eitner (1986), in general it is not possible to deduce a correlation between odor perception and carbon content. Therefore, strongly smelling sulfur or nitrogen compounds are not collected during the measurement of total carbon, whereas the measuring instrument registers odorless methane.

Both observations show that, for the time being, the sensory measurement method of olfactometry, i.e., odor perception by humans, is still the best method in order to evaluate odors from biological waste treatment plants.

The analysis of the total carbon content of the sample air by means of an FID was carried out simultaneously with most of the measures for odorant concentrations. However, an evaluation of a correlation with the odorant concentrations was not carried out.

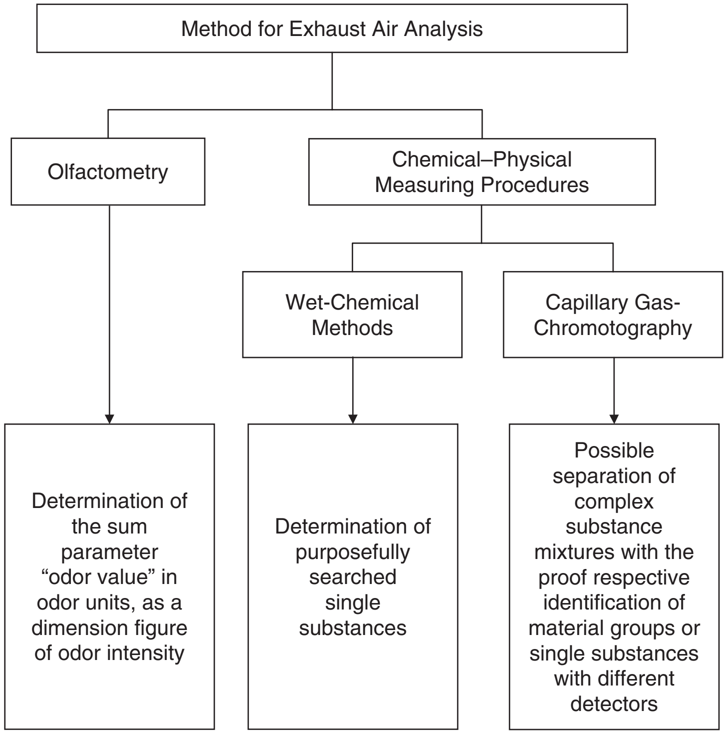

Fig. 11.2. Survey of the methods for the analysis of exhaust air (Eitner, 1986).

The reasons are as follows:

- Gases, such as methane, are also detected with the FID. These gases contribute to the sum parameter TOC in (mg C/m^3), but, on the other hand, the gases are non-odorous.
- Odor-intensive substances, such as ammonia, do not have an FID value.
- A correlation between FID value and odorant concentrations may be valid for specific units in a composting plant (e.g., the biofilter) or even for entire plants after the calibration of the measurement system for the particular type of plant or plant location, but it is not the case for most of the results of the measurements used here.

Considering a correct evaluation and classification of the measurements contained in this chapter, it must be said that the statement of different concentrations of odorants does not give any indication of the hedonic odor intensity, i.e., about the quality of the odors measured (pleasant versus annoying). Furthermore, it has to be pointed out that a tenfold increase of the odorant concentrations only corresponds to a duplication of the perceivable odor intensity, since the human nose perceives the sensation "smell" only on a logarithmic scale according to its intensity. Therefore the measured concentration is shown in a logarithmic scale (see Table 11.1):

$$[\text{dB OD}] = 10 \times \log_{10}[\text{OU/m}^3]$$

The dependence of the intensity of the odor emission on the ambient temperature is mentioned here as a last factor relevant to the evaluation of odor data. Since the substances that lead to odor impressions are volatile, the temperature of the source of the odor (e.g., windrows) is a significant variable. Odor-intensive, intermediate degradation substances in their utmost concentration are present during the "hot" first phase of the composting process.

11.2.2.2. Olfactometry

According to VDI Guidelines 3881 sheet 1 (Anonymous, 1986a), olfactometry is the controlled performance of odor carriers and the collection of sensitive sensations caused in man by this process. That means that this measurement method does not show the amount of odor carriers, but the effect of these individual particles on the human being.

Olfactometry is the current method of determining odors that offers results close to reality. Olfactometry is currently the only possible odor determination method, as odor perceptions can be triggered even if the corresponding concentrations cannot be determined with chemical–physical methods. The following characteristics of odor are determined by olfactometry (Anonymous, 1986a):

- odorant concentration;
- odorant intensity;
- hedonic tone; and
- quality.

The odorant concentration of the gas sample to be measured is determined by dilution with neutral air down to the odor threshold. The numerical value of the odorant concentration in OU/m^3 (odor units per m^3) results from the volumetric flow of the gas sample and the neutral air at the instant when the odor threshold is reached.

Table 11.1. Correlation between odorant concentration and odor intensity

Odorant concentration (OU/m^3)	Odor intensity (dB OD)
10	10
100	20
1000	30
10,000	40
100,000	50

The odorant concentration must be judged differently from the odorant intensity. It is a dimension of the strength of the odor sensation (similar to sound sensation), where the absolute but not the relative changes are perceived.

As with nearly any other measurement method, olfactometry sample collection is an essential criterion for quality assurance (QA) of the results of the measurement. Basically, one must distinguish between two different sampling techniques:

- dynamic sampling and
- static sampling.

Dynamic sampling provides that a partial flow of a source is conveyed directly and continuously from the source to the olfactometer.

Static sampling provides that an odorous gas is filled into an odorless vessel (usually a plastic bag) and is then examined with the olfactometer.

According to VDI Guidelines 3881, in order to avoid errors during sampling, the following must be observed (Anonymous, 1986a):

- avoid the formation of condensate by pre-dilution with dry and odorless air,
- no particles should enter the olfactometer,
- one has to ensure the absence of odors in the sampling system, and
- chemical reactions between the components, as well as sorption at the walls of the sampling system, should be avoided during transport from the sampling location to the olfactometer.

In addition to the method of sampling, the selection of the panelists (test persons) is of utmost importance for the assessment of the measurement results.

The sense of smell of the panelist can be tested with the help of standardized odorous compounds. One of the typical standard odorous materials is hydrogen sulfide (H_2S). The odor threshold with H_2S determined through inter-laboratory tests lies within the limits of $0.60\,\mu/m^3$ < test results <$15\,\mu/m^3$. If the results of the reference tests of the panelists fall within these limits and meetall of the other requirements, they are satisfactory to the actual requirements of an olfactometric measurement. Additional information about sample collection can be obtained in the VDI Guidelines.

Odorant Concentration

The determination of the odorant concentration is based on the concept that the odor intensity of the sample to be tested increases when more of the sample must be diluted in order to reach the odor threshold. The odorant concentration at the odor threshold is the dilution ratio between odorless air and the sample to be tested, whereby 50% of the panelists realize an odor impression and the other 50% do not. This concentration is defined as odor unit per cubic meter ($1\,OU/m^3$).

Contrary to most of the other measurement methods (e.g., for dust measurement), knowledge of the sample composition is not necessary for odor determination. However, the quantity or quality of the sample must not change before the measurement.

A mathematical description of the concentration is as follows:

$$c_{G,P} = 1 + \frac{V_N}{V_P}$$

$c_{G,P}$ odorant concentration in OU/m^3,
V_N volume percent odorless air, in volume per time unit,
V_P volume percent sample, in volume per time unit.

Odor Intensity

Since the concentration at the perception of odor above the odor threshold is not a sufficient criterion for the assessment of an odor impact, the odor intensity among others is determined as well. The intensity can, theoretically, be calculated through the relationship between odor intensity and odor concentration.

When immissions are measured in the field, the odor intensity is determined by means of inspection. The determination by olfactometer is performed under the same conditions as those for the determination of the odor threshold. The procedure is described in the VDI Guidelines 3881 sheets 1–4 and 3882 sheet 1. The determined stages of intensity range from not perceptible (0) up to extremely strong (6), as described in Table 11.2.

Odor Quality (Hedonic Tone)

The hedonic tone of an odor is quite important in order to determine odor annoyance. The odor can be described as from "very comfortable," through "neutral," to "very uncomfortable" (see Table 11.3). The human perception can be determined more exactly through

Table 11.2. Stages of odor intensity

Odor	Intensity stage
Not perceptible	0
Very faint	1
Faint	2
Distinct	3
Strong	4
Very strong	5
Extremely strong	6

Table 11.3. Scale of the hedonic property (Anonymous, 1994a)

−4	−3	−2	−1	0	+1	+2	+3	+4
Extremely annoying				Neither annoying nor comfortable				Extremely comfortable

the quality of an odor. According to Henning (Cooperative, 1992), odors are classified into six basic types: flowery, putrid, fruity, spicy, burning, and resinous.

The hedonic tone can be determined at emissions and immissions by means of panelists. The German Odor Immission Guideline (GIR, 1993) does not provide a determination of a hedonic odor impact. Because of the substantial dependency on the odor properties of the individual panelists, at least 15 panelists must be engaged (Anonymous, 1994a).

Before an odor investigation is started, a preliminary threshold destination should be carried out to assess the range of concentration. The sample presentation must be carried out following the constancy method (dilution stages in random order). The first concentration stage has to be adjusted in the medium range. In addition, check plots can be mixed in. The panelists shall indicate if they smell something at all and afterwards assess the hedonic property according to the scale shown in Table 11.3.

11.2.3. Reasons for Odor Generation in the Composting Processes

When objectionable odors are generated, it is necessary to differentiate between aerobic and anaerobic processes. Since odor emissions from composting are the subject of this chapter, only the aerobic biochemical processes are discussed.

Composting of biowastes is mainly a microbiological, catalytic degradation and transformation process. Within this process, four dissimilarly long-lasting phases (temperature development) can be considered (Fig. 11.3) (Kuchta, 1994):

- mesophilic (starting) phase;
- self-heating phase;
- thermophilic phase; and
- maturation phase.

According to Schildknecht and Jager (1979), the various phases can be classified into three odor ranges of aerobic biochemical odor formation at composting:

- waste smell, odor substances of the original products;
- biogenic odors; and
- abiogenic odors.

The classification of these three ranges is shown in Fig. 11.4.

Mesophilic Starting Phase

The smell of the original substrate (waste) is determined by specific substances in the waste. It is mainly generated in the mesophilic starting phase during discharge, at the storage and treatment of biowaste, and at the beginning of the composting process. The odors arising from the material are not only dependent on its organic components but also to a substantial degree on the fact that the biowaste is already in the process of decomposition at the time of supply, or the treatment of the biowaste has not been properly carried out.

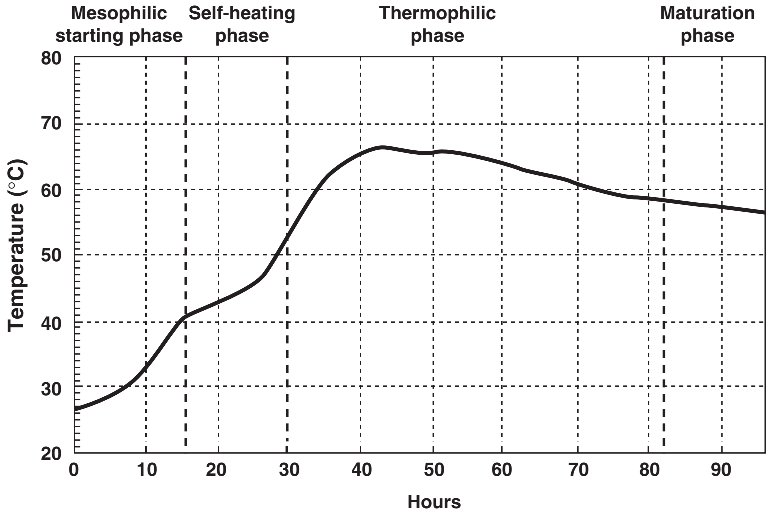

Fig. 11.3. Experimentally determined temperatures during composting (decomposition test in a Dewar vessel) and allocation to the various process phases.

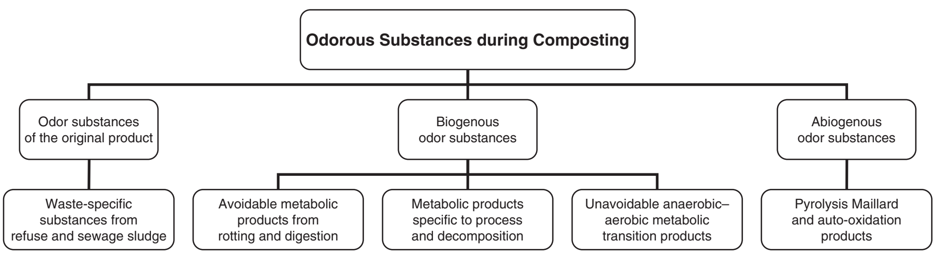

Fig. 11.4. Odor substances during composting (Jager et al., 1995).

The odor is caused by such components as limonia, terpene, and intermediates of anaerobic degradation processes (Kuchta, 1994).

During the starting phase of composting, substantial portions of easily degradable organic substances are decomposed. These substances are mainly decomposed by mesophilic microorganisms residing in fresh biowaste using considerable oxygen. Thus, the available oxygen in the substrate is prematurely used. The diffusion of oxygen from the ambient is not enough to reach deeper areas of the mass, so anaerobic degradation processes arise increasingly.

Aeration of the material during decomposition improves the oxygen input; this means that the volatile substances are more easily released into the atmosphere, which leads to a heavy odor load in the ambient air.

Self-Heating Phase

Because of the increasing biological activity followed by an increasing temperature, the mesophilic microorganisms are replaced by a thermophilic heat-loving population. Additionally, the high-temperature level releases less volatile biogenic odor components. A lack of oxygen during this phase preponderantly causes anaerobic processes. Thus, the aerobic–anaerobic metabolic transition products together with the metabolic products of rotting and fermentation phases are increasingly responsible for the odor emission. The rotting and fermentation metabolic products, which can be avoided, arise above all through unnecessarily long detention times in the bunker.

Unavoidable odors are those arising from the anaerobic and aerobic transition products and the process-related metabolic products, which are generated during decomposition by turning or aeration of the windrow. The development of the microorganisms in the decomposing material sometimes causes a fractional lack of oxygen (e.g., in small anaerobic voids). A 100% aerobic decomposition is very difficult. The microorganisms transform their metabolism because of the anaerobic zones and form the odor-intensive, anaerobic–aerobic intermediate products (Jager et al., 1995). These odorant substances are released by the turning of the windrows.

Thermophilic Phase

As the easily degradable substances in the biowaste decrease during the decomposition period, a decrease of the formation of biogenic odor components follows. However, abiogenic odor substances are simultaneously generated, which are released via a purely chemical means — through pyrolysis, auto-oxidation, and Maillard products. Their formation grows with increasing temperature (Eitner, 1986). A very annoying odor (sweet–spicy) with a very low threshold value can arise at temperatures of about 80°C during the first 2 weeks of decomposition (Nithammer, 1995). Such substances can be perceived over long distances.

Maturation Phase

Increasingly, the more medium and difficultly degradable components of biowaste are decomposed during the last phase of composting. This changes the properties of the decomposed material, resulting in a decrease in microbiological activity and a temperature decline. The progressive decrease in oxygen consumption causes a new aerobic environment, and the odor emissions decrease.

According to Pöhle et al. (1993), the process regarding the released odorant substances over the total decomposition period can be classified into three phases. The three phases and their characteristics are described in Table 11.4.

Table 11.4. Phases and odor-active substances of the decomposition process (according to Pöhle et al., 1993)

Decomposition phase	Characteristic odor-active substances	Determining odor impression	Concentration (OU/m^3)	Period (days)	pH value
I. Acid starting phase	Aldehyde, alcohol, carboxylic acid ester, ketone, sulfide, terpene	Alcoholic — fruity	6000–25,000	3–14	4.3–6.0
II. Thermophilic phase	Ketone, sulfide-organic compounds, terpene, ammonia	Sweet — fungoid, annoying — musty	1000–9000	4–14	Limit to the basic range
III. Cooling phase	Sulfide, terpene, ammonia	Musty — fungoid — pungent	150–3000	To the end of the test period	–

11.3. Determination of Odor Flow Rates and Odorant Immission

According to the German Federal Immission Control Act for Ambient Air (BIm-SchG, 1990) and under the fulfillment of appointed criteria, odors are subject to the category of considerable annoyances. Odors have to be avoided by order of law in the frame of new emitting plants, i.e., prophylactic, or by the order of subsequent measures by existing plants (Both et al., 1993).

Despite the fact that the perception of noises and odors are very similar, the assessment of odors is by far more difficult than that of noise. While the measurement for noise can be carried out with distinct physical methods, the odor measurement cannot be done without the sometimes unreliable “detector” — the human being.

The question of whether or not odor annoyances have to be looked upon as being harmful environmental impacts not only depends on the immission concentration but also on the type of odor, the distribution of the impacts during the day and year, the location where the annoyances arise, the use of the surrounding area, and other criteria (GIR, 1993).

At the moment, the GIR of the Federal State of North Rhine-Westphalia is the basis for the measurement of odor emissions and their assessment. It is now recommended for application in all Federal States of Germany.

11.3.1. Dispersion Mechanisms of Odors

Olfactometric measurements allow statements about odorant concentrations at the point of the emissions. However, no statements can be made regarding immissions. Therefore, it is of importance to describe the mechanisms for spreading odors in the atmosphere.

Two different sources of odor have to be distinguished:

- defined sources and
- diffuse sources.

Defined sources have known emission conditions such as:

- location of the site;
- time of emission;
- height of source of emission (e.g., height of chimney);
- upper width of the source;
- exhaust air velocity and quantity; and
- exhaust air temperature and humidity.

The determination of the exhaust airflow of diffuse sources is very difficult; however, the flow can be roughly estimated. Thus, many sources at composting plants can be considered to be diffuse sources. The uncertainty condition of a multitude of factors makes an assessment of the dispersion situation very complex.

When odor loads are determined, one has to differentiate between active and passive sources.

Active odor sources, like the biofilter, are structural components or units of a plant through which a defined volume of gas flows for the purpose of aeration; during its passage through the system the gas loads itself with odorants (Homans, 1993). In case the odorant concentration is measured with an olfactometer or an FID together with the air quantity, the odor load can be calculated fairly accurately.

Passive odor sources, on the contrary, are mostly large surface areas (e.g., windrow surfaces) to which a defined volume of flow can be allocated during the measurement at the odor outlet. Thus, a determination of the air load at the source is very difficult to achieve. In order to determine this air load, hoods or tents are usually placed over a defined area on the emitting surface and after an appointed time, the odorant concentration can be determined.

To obtain a representative result, Harkort (1989) recommends partitioning the areas into four representative sections and taking samples from the focal points of the surfaces. By these means, fissures, crude gas offtake, edge fringing, and irregularities of the fill can be ascertained. An artificial mass flow of air can be caused with this method, which influences the thermal conditions in the windrow and which only allows an approximation of the actual odor loads. This means for the dispersion calculation that the precision of the prognosis of the immission deteriorates with an increasing number of passive sources.

Beside the aforementioned factors, dispersion behavior of air admixtures is also dependent on the height of the source since air pollutants fundamentally expand and dilute in the horizontal and vertical planes of the space. Since odor sources from composting facilities mostly originate from sources close to the ground, it has to be considered that the vertical dispersion toward the ground is limited and, thus, concentrations are generated in the upper half of the space, which are twice as large, contrary to a dispersion to all sides of the space (assumption of the Gauss models of a full reflection at the ground) (Schultz, 1986). The dispersion behavior of emissions near the ground is shown in Fig. 11.5.

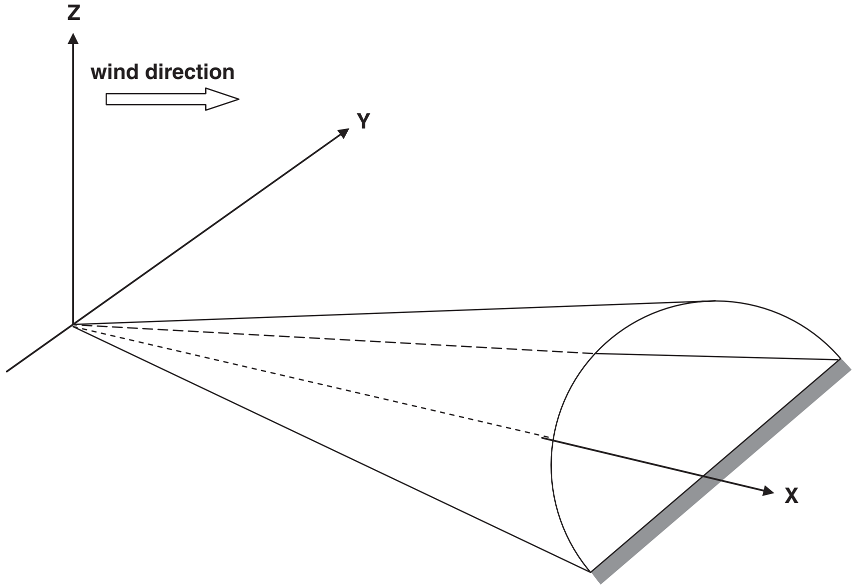

Fig. 11.5. Half conical dispersion near the ground (Engelhardt, 1982).

As shown in Fig. 11.5, odor dispersion is a tri-dimensional phenomenon, which takes place within an air layer near the ground surface, which is called the mixing layer. In the first instance, the height of the layer depends on the temperature conditions. A nearly stable air pressure condition is prevailing above this mixing layer, so that its upper boundary behaves like a lid and no upward air exchange takes place (Köster, 1996).

The following parameters influence the transport of gases emitted from an odor source:

- wind direction and velocity;
- temperature;
- air pressure;
- cloudiness;
- insolation; and
- local conditions such as location on slopes, plants, type of buildings, and water bodies.

If the wind velocity is constant, the odor distance (odor plume) usually becomes shorter toward the wind direction of a source with rising height of the mixing layer and increasing degrees of turbulence. Since both factors are influenced by the intensity of insolation, the odor distance is subject to seasonal and daily fluctuations. Dispersion in the horizontal direction is mainly determined by the wind velocity (Köster, 1996).

In sunny weather and the resulting large vertical temperature drop, the odor is perceivable only over short distances depending on the increasing height, the mixing layer, and high wind velocities. Toward the evening or at night, the temperature profile becomes more uniform due to a lack of insolation, which concentrates the odor. In this situation, the odors can also be perceived over long distances (Krämer and Krause, 1977). Proof for this phenomenon is that most of the complaints about odor annoyances are made between 6 and 12 pm (Frechen, 1988).

Very unfavorable conditions exist for odor dispersion during periods of atmospheric inversion. Contrary to the normal situation when the air temperature increases with increasing height, an inversion of the temperature gradient takes place. The warm air volume above the cooler air layer near the ground does not allow a vertical exchange.

During summer, an evening inversion layer usually dissolves itself in the mornings after a short amount of insolation. In the winter, however, it can happen that the insolation is not intensive enough and the inversion can be broken down only through a weather change and/or upcoming winds (Engelhardt, 1982).

An additional factor that has to be considered is the topographic location of the sources. The temperature rise of the air is higher in valleys, whereby emission-relevant valley breezes are generated. Furthermore, the contour of the ground surface has to be considered as the flow of the air close to the ground conforms itself to the ground surface. The dispersion situation above lakes, rivers, or large, connected buildings, which serve as heat accumulators, can also be changed (Engelhardt, 1982).

Composting plants are considered to be a source near the ground whose emissions do not have an ascending force (i.e., cold sources). Consequently, the dilution of the emitted odorant substances is mainly in the horizontal direction. As opposed to a source that is high (such as a chimney), the vertical dispersion from the source near the ground is possible only in one direction. This leads to the fact that odors can be perceived over long distances because they can be transported with little dispersion along their path of flow.

The situation described above becomes more problematic if the climatic conditions also consist of low wind velocities and little atmospheric vertical substitution; the situation deteriorates additionally and the immission concentrations increase considerably (inversion weather condition) (Müller and Obermeier, 1989).

11.3.2. Determination of Odorant Immissions

According to GIR (1993), an odorant immission is to be assessed as such if its origin is clearly coming from plants, i.e., can be isolated from odors resulting from traffic, domestic coal combustion, vegetation, agricultural fertilizing activities, or other similar generators of odor (GIR, 1993).

In fact, there are different methods for the assessment of the relevance of an odorant immission (Table 11.5). In all cases, the odorant immission is characterized through a value, which describes its time-dependent perception above a certain intensity (recognition threshold).

For each plant to be approved, the GIR, just as the Technical Data Sheet Air (TA-Luft), demands an assessment of the existing load (IV) before the plant is set up and the additional load (IZ) that is expected to be emitted by the plant. Both are added to a total load (IG)

Table 11.5. Methods for the determination of odor immissions (GIR, 1993)

Method	Existing load	Additional load
A	Olfactory determination of the odor immission through panelists and determination of the frequency distribution	Calculation of the odor immission (OU/m^3) from the emission of the odorant flow (OU/h) and determination of the frequency distribution
B	Chemical–analytical measurement of the immission concentration of an odorant ($\mu g/m^3$) determination of the frequency distribution	Calculation of the immission concentration of an odorant from emission data determined chemically or analytically and determination of the frequency distribution (dispersion calculation)

and then compared with the immission values for residential and mixed areas (Table 11.6) and tested if exceeded.

As opposed to the Technical Data Sheet Air (TA-Luft), the GIR compulsorily prescribes the determination of the existing load (IV). Usually, it is determined with the help of field measurements using odor panels (Anonymous, 1993a).

11.3.2.1. Field Measurements Carried Out by Panelists

The size and shape of the area to be tested must be determined before the panelists start their assessment. According to use and type of the odor source, they are different depending on the use of the area and type of the odor source. Following GIR methods, the test area must be designed in such a manner that the minimum distance from the border of the area source will be 600 m. Thereafter, the area is divided in a square assessment grid with distances of 1000, 500, 250, or 125 m; the guideline provides a distance of 250 m. Measurement points that are not favorably situated can be moved by a maximum of 25% of the grid width. Measurement points in areas where people are very rarely present (e.g., agricultural areas) can be omitted.

According to VDI Guideline 3940, the period of assessment is one year and only in exceptional cases half a year. The GIR Guideline for the protection against immissions deems a representative period of half a year as being sufficient. Within the period of assessment, either 13 or 26 independent individual measurements must be carried out,

Table 11.6. Immission values, quoted as relative limit values for different settlement types (GIR, 1993)

Residential/mixed area	Commercial/industrial area
0.10 (10%)	0.15 (15%)

(In parenthesis: data in percentage of the annual hours.)

according to the requirements per measurement point and depending on measurement duration. There are in total 52 or 104 measurement days per test area, depending on measurement duration. To make the measurement representative, season of the year, the weeks, and the days of testing must be adequately considered (weekend, public holidays, night) (Nithammer, 1995).

The inspection of the assessment squares has to be arranged in such a sequence so that neighboring measurement squares are inspected on different days. This method assures that in each case the assessment for each assessment square and each measurement period carried out on 4 different measurement days enters the determination of the characteristic quantity (GIR, 1993).

The panelists determine perceivable site-specific odors on the site, if necessary, differentiated for different qualities of odor. The odor impression is made by a yes/no answer to a question ("yes, there is a smell" or "no, there is no smell"). The intensity of the odor and the hedonic tone are not determined.

The specific individual odor sensitivity of the panelists must be tested before they are allowed to perform the odor assessment. Those panelists whose odor threshold for hydrogen sulfide has been determined olfactometrically and is greater than 6 or less than 1.5 $\mu g/m^3$ must be excluded from the measurement (GIR, 1993).

In order to describe the frequency and time of odor occurrence, the panelist must stay at a measurement point for 10 min. Within this period, he or she examines the site for perceivable odors. Two methods for the measurement of the perceived odors within the time interval can be used (Both et al., 1993):

1. The time from the beginning until the end of the odor is recorded by means of an electronic recording device. When 10% of the time of the measurement interval with odor is reached, the criterion of an odor hour is fulfilled.
2. The odor inquiry is carried out by clock frequency (10-s clock frequency), i.e., six times per minute or 60 times for a sampling period of 10 min. When 6 clock frequencies with odor are reached, the criterion of the odor hour is fulfilled.

Remaining for a period of 10 min at the measurement point is looked upon as being representative of a hypothetical stay of 1 h; the term "odor hour" is based on this criterion.

The field measurement method by means of panels records the odor immission situation in a certain area in the form of a frequency of odor hours. The existing load can be calculated with the following formula:

$$\mathrm{IV} = k \cdot \frac{n}{N}$$

N duration of sampling period
n sum of odor hours
k correction value (Table 11.7).

The **expected additional load (IZ)** is determined by means of a dispersion calculation. This calculation has to be carried out according to Guideline VDI 3782 sheet 4 on the

Table 11.7. Correction value k as a function of the scope of sampling N and the type of settlement (GIR, 1993)

Scope N	Residential area/mixed area	Commercial/industrial areas
52	1.7	1.6
104	1.5	1.3

basis of 1 OU/m^3. The formula for the calculation of IZ is as follows:

$$\mathrm{IZ} = \frac{n}{9 \times 8760}$$

n sum of the odor hours at the 9 measurement points of the assessment area,
8760 number of hours per year.

The expected **total odor load** is determined by the arithmetic addition of IV and IZ:

$$\mathrm{OL}_{\mathrm{tot}} = \mathrm{IV} + \mathrm{IZ}$$

Despite an existing or expected exceedance of the immission values, plants can be approved for operation if the additional load (IZ) is not more than 20% of the permitted immission value for residential and mixed areas (irrelevance criteria) (Both et al., 1993).

11.3.2.2. Plume Inspection

The typical method for the determination of a site-specific odor in the neighborhood of an emission source is the plume inspection. The odor plume of an emission source is the area where the odor frequency is 5% or higher. The plume limit is reached per definition if the odor frequency or the odor time rate is 10%. The plume axis is the line in the direction of the distribution where the maximum of the odor frequency or the odor time rate is detected near ground level. As a rule, it coincides with the wind direction. The wind direction is measured 2 m above ground level (potential immission area) (Anonymous, 1993a).

The total measurement consists of three intersectional measurements vertical to the spreading axis with 5 measurement points each or/and 5 panelists (Fig. 11.6). The measurement time should be 10 min and should be conducted at 90° to the actual wind direction. The distances are subject to the expected spreading of the odor plume; however, they must not be equally large.

The dispersion of the odor plume is determined by:

- the size of the emission source;
- the odorant flow rate;

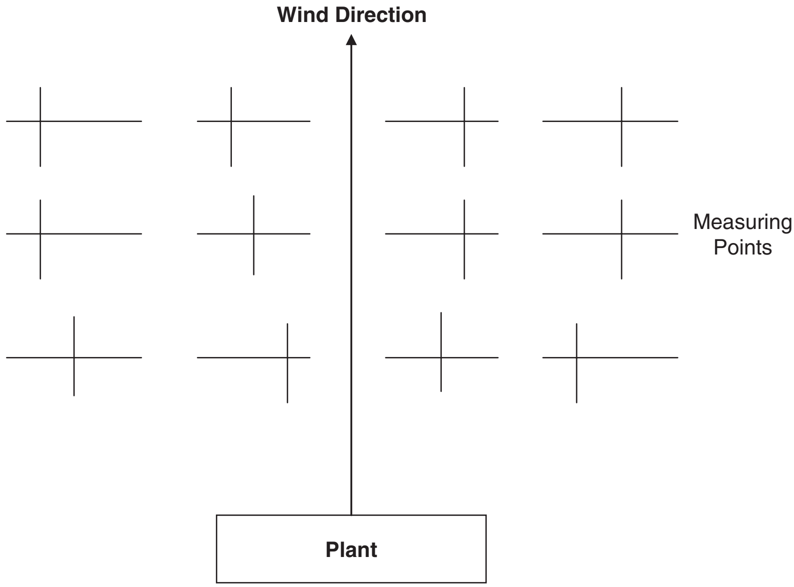

Fig. 11.6. Arrangement of the measurement points of the plume measurement on the leeward side of the source (Anonymous, 1993a).

- the spreading parameter;
- the building area; and
- the topography.

The plume measurement method is suitable for the calibration of an odor dispersion model, where calculated concentration values that were determined by plume measurement are compared. This method, in particular, is used if the measurements of the odorant flow rate must be compromised because of difficulties arising from measurement techniques (diffuse sources, sources spread from areas).

11.3.2.3. Dispersion Calculation

The flow rate of an odorant from a plant is determined by olfactometric plume inspection. The bases for the calculation of the dispersion are odorant flow and the statistics of the dispersion class intervals (meteorological data), representative for the location. The statistical data are usually determined by the German Weather Service over a period of 10 years. According to TA-Luft (Technical Data Sheet Air), the transferability of the meteorological data to the individual location of a plant must be examined (TA-Luft, 1996). This is especially true for the distribution of wind direction, as described in Section 11.3.1, Dispersion

Mechanisms of Odors, which is of special relevance. Wind direction measurements onsite should be carried out for control purposes in order to modify the statistics of the dispersion class intervals, if necessary.

Being the basis for the dispersion calculation, it is of special importance that the previously determined emission data be accurate. The dispersion calculation itself is not free from errors. According to Both (1992), errors are introduced due to the use of the factor 10 in the TA-Luft-Model. Besides the TA-Luft-Model, the model according to the VDI Guideline 3782, sheet 4 is used for the odor dispersion. A new model (DASIM-ODEUR) has been developed at the Technical University of Darmstadt. The model, however, has not been fully utilized, but will remove the weak points of the TA-Luft-Model. According to Manier (1994), the decisive mistake of the TA-Luft-Model is that a wind field is assumed to be spatially constant, but this assumption does not coincide with reality. Wind direction and wind velocity change with altitude. Local ground roughness also influences a change in the horizontal level of the wind field. According to Manier (1994), the TA-Luft can no longer be considered state-of-the-art.

Since the new DASIM-ODEUR model is not generally used at the moment, the following discussion is based on the other two models that were also discussed in the previous paragraph.

Both the immission concentrations from which the odor frequencies are calculated and the immission time assessment must be given for the calculation of the odor dispersion. These calculated values must be compared with the limit values. At present, the given values differ between 1 and 10 OU/m^3, at 3 and 6 min, respectively. A calculation threshold of 1 OU/m^3 and an immission time assessment of 6 min will be implemented in the planned immission guidelines.

Additional parameters include:

- the height of the source in meters;
- the elevation of the exhaust gas plume in meters;
- the emission time in h/year;
- the coordinates of the source; and
- the odorant flow rate (odor load) in Odor Unit/hour

The odorant flow rate q_G to be determined is the product of the concentrations c_G determined by olfactometric means and the volume stream V. In the case of composting plants, where there are many source areas that are difficult to determine, the odor loads can also be ascertained by a combination of the dispersion calculation and panelists (Kettern and Köster, 1992).

$$q_{Gi} = c_{Gi} \times F_i \times f$$

q_{Gi} (OU/h)	odorant flow rate of the ith area source,
c_{Gi} (OU/m^3)	measured odor concentrations ith area source of odors,
f (m/h)	proportionality factor,
F_i (m^2)	area of the ith area source.

The odor frequencies of the relevant odor emitters on the leeward side are determined by panelists. The proportionality factor "f" in the dispersion calculation is varied until the squared deviation between the calculated frequencies of the perceptions and those made through field measurements reach a minimum. The mean factor, $f = 10$, can be determined through quite a number of field inspections on several composting plants (TÜV, 1992).

11.3.2.4. Questioning of Residents

Today it is still very difficult to determine the relationship between material emissions, perceptions, and odor annoyances when new plants are planned. The determination of already existing annoyances is less problematic. The following three methods are available to perform the determination (Nithammer, 1995):

1. acquisition of complaints (statistics involving number of complaints),
2. systematic single questioning in defined assessment areas with questionnaire, and
3. systematic multiple questioning of panelists living in the area regarding determination of frequency and temporary occurrence of the odor impacts (Anonymous, 1994a).

Frequency and degree of annoyances can be determined in an assessment area by means of questionnaires. The systematic one-time questioning is carried out in one area over a longer period of time. A representative opinion in the population can be ascertained using this method. A systematic multiple questioning is preferably used when individual odor occurrences are perceived. The questionnaire contains the following information:

- frequency and duration of odor impacts;
- subjective classification of the perceived annoyances and tolerable acceptance of annoyances;
- reaction and changes of behavior;
- sources and time of odor immission; and
- satisfaction of the inhabitants with the surrounding environment.

11.4. Assessment and Comparison of Odor Data

The determination of odor data by means of an olfactometer has been available for a number of years. The methodology, equipment, requirements, and measurements, together with the legal standards, for odor measurements changed remarkably during those years. This and the fact that each measurement is carried out under different conditions (different panelists, different seasons for the measurement of samples, e.g., summer/winter, etc.) are leading to the fact that individual measurements can seldom be compared successfully with each other.

The difficulty of comparability is influenced by the following factors:

- measurements taken by different institutes,
- measurements taken during different climatic conditions,

- measurements taken by panelists of different ages, and
- measurements taken with different olfactometers and different panelists.

Measurements Taken by Different Institutes

Mannebeck and Paduch (1992) carried out an inter-laboratory test with four test institutes [IPT 1158, TO6, Ströhlein, and MEO 5 (Essers, 1992)] with different olfactometers. Two odorants were used in the test, *n*-butanol and dibutylamin. Each test institute received both odorants in three concentrations and in three replications in a 50-l bag made of nalophan. The order of the individual concentrations was not known to the panelists. The only requirement was that the number of panelists be limited to four.

The data in Table 11.8 show the dilution numbers of the calculated odor thresholds in micrograms/cubic meter taken by four different panelists for two odorant substances and different concentrations (Both, 1993). The results determined by one test institute show a maximum deviation of the odor thresholds for *n*-butanol by a factor of 6 (test person D) and for dibutylamin by a factor of 4 (test person A and D).

A comparison of the results among the test institutes shows that there is a maximum deviation of a factor of 8 for *n*-butanol and of 15 for dibutylamin. Furthermore, the data in Table 11.8 prove that no correlation exists between the determined odor thresholds and the flow rate concentrations of the odorant. As a result, the nine measurement values can be considered similar to the results from repeated measurements.

Results from field inspections performed by different test institutes may also be subject to deviations. The Institute on the Protection against Immissions in Essen carried out an inter-laboratory test in 1994 with field measurements by panels (Both, 1993).

Table 11.8. Odor thresholds (μg/m^3) of the panelists (A, B, C, D) per bag sample (= single measurement) (Both, 1993)

n-Butanol		Odorant flow rate concentrations (mg/m^3)								
		970	970	970	1940	1940	1940	3880	3880	3880
A	μg/m^3	216	137	115	218	162	121	259	228	194
B	μg/m^3	237	651	439	362	710	585	230	338	273
C	μg/m^3	334	571	539	539	451	669	456	579	539
D	μg/m^3	545	405	428	212	84	128	342	440	179
Dibutylamin		**Odorant flow rate concentrations (mg/m^3)**								
		455	455	455	910	910	910	1820	1820	1820
A	μg/m^3	331	1138	687	535	827	506	520	289	700
B	μg/m^3	1813	1813	1850	3840	1358	3043	2510	4313	1209
C	μg/m^3	1422	1422	1468	1685	1282	1444	1517	1400	1400
D	μg/m^3	870	636	1207	1058	1020	1162	1844	2642	1584

Between June and October 1989, a total of 52 field measurements were carried out at 45 appointed assessment squares, with a total of 60 assessment points with a grid spacing of 500 m. Each test institute used its own team of panelists.

Based on the results of the tests, it can be stated that the method of field measurements for the evaluation of odor immissions is fundamentally suitable since all of the panelists found a decreasing odor immission load with increasing distance from the source. However, the comparability of these results is open to question (Both, 1993).

Fig. 11.7 shows the result of an inter-laboratory test, where the determined odor frequencies (in% of the annual hours) have been calculated by three different institutes as a function of the distance to the emitter.

The curves in Fig. 11.7 show that there is a considerable difference between the results of the measurements made by institutes A, B, and C, which, in the mean, is a ratio of 1:2:3.

The results lead to the following quality criteria for field inspection:

- standardization of the measurement method, e.g., by defining the criteria for the selection of panelists and a directive for the training of panelists, and
- carrying out additional field measurements.

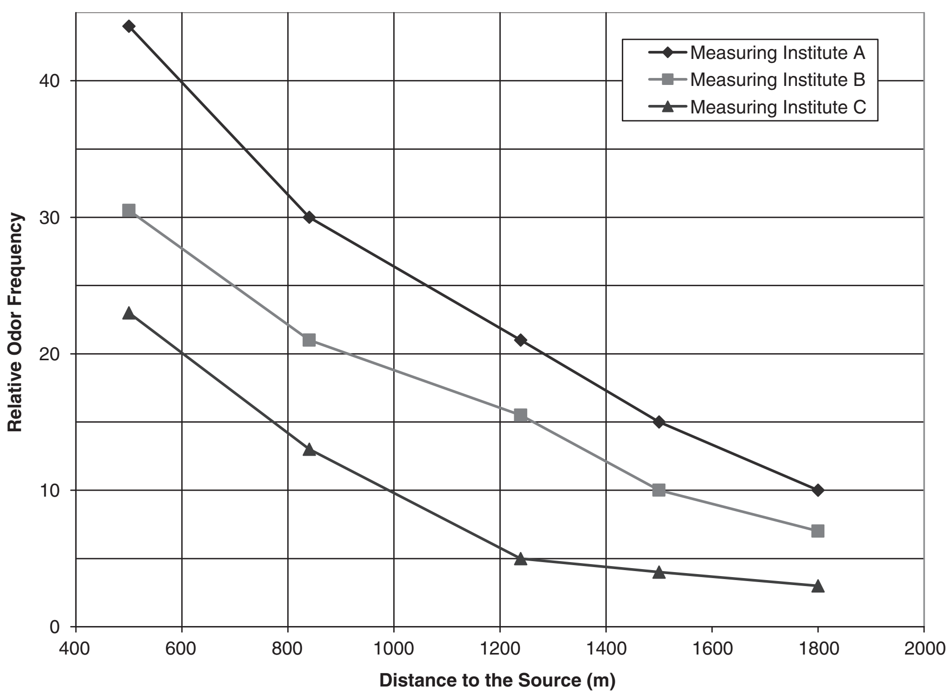

Fig. 11.7. Determined odor frequencies measured by different institutes (Both, 1993).

Measurements during Various Climatic Conditions

Proper assessment of odor data requires a good understanding of the temperatures at which the odor measurements were carried out since the substances that induce odor perceptions are substances that are highly volatile. Volatility is strongly dependent on temperature, not only the temperature at the odor source but also the ambient air temperature. During summer months, substantially higher odorant concentrations are released from a composting plant than during winter season. In many cases, odor analyses do not clearly indicate the time of year of the odor measurements.

Measurements with Different Age of Equipment

The problem of measurements with different age of equipment must also be realized when reviewing and analyzing odor data acquired using olfactometers. Like any other technology, olfactometers have been improved over the years.

Measurement with Different Olfactometers and Panelists

The comparison of olfactometric measurements, even if two identical olfactometers are used, is dependent on a number of factors, which cannot yet be qualified and quantified. These factors can be defined as follows (Jager et al., 1995):

- ambient temperature (sample taking/laboratory/sniffing sample);
- air humidity (sample taking/sniffing sample);
- air pressure;
- age of the panelists;
- physiology (effect of the sense of smell, partial anosmia from influenza); and
- personal habits and lifestyle (e.g., smoking).

According to Habenicht (1992), odor threshold concentrations of hydrogen sulfide (H_2S) between 0.08 and 8 $\mu g/m^3$ can be determined by a team of panelists used for this purpose. Values of 0.3–15 $\mu g/m^3$ are indicated by the VDI guideline 3881: other literature sources quote values between 0.06 and 63 $\mu g/m^3$. The data in Table 11.9 show the variation of odor thresholds within one team of panelists. As shown in the table, the threshold values vary with increasing odorant concentrations. It is surprising that the odor threshold reaches the highest level when the concentration is lowest.

Fig. 11.8 shows comparative tests of odorant concentrations with two olfactometers, TO6 and IPT 1158, in relation to each other (Habenicht, 1992). The data in the figure clearly show substantial differences (ratio TO6 to IPT 1158) between the concentrations when the odors were perceived as faint (less than 1000 OU/m^3). Differences between both olfactometers could be determined, varying up to fourfold (3.93) in the case of faint odors, and the concentrations measured with TO6 were always higher than those with IPT 1158. Strong odor perceptions (greater than 10,000 OU/m^3) measured with TO6 resulted in a 3-fold (2.96) higher odorant concentration than those measured with IPT 1158.

Even the same team of panelists determined different odorant concentrations during one day (Table 11.10). These differences result from the aforementioned factors.

Table 11.9. Odor threshold variation of a panelist team, dependent on concentration (Habenicht, 1992)

H_2S (mg/m^3)	Odorant concentration (OU/m^3)	Odor threshold H_2S (µg/m^3)
28.40	12,200	2.32
14.20	5800	2.45
2.84	920	3.08

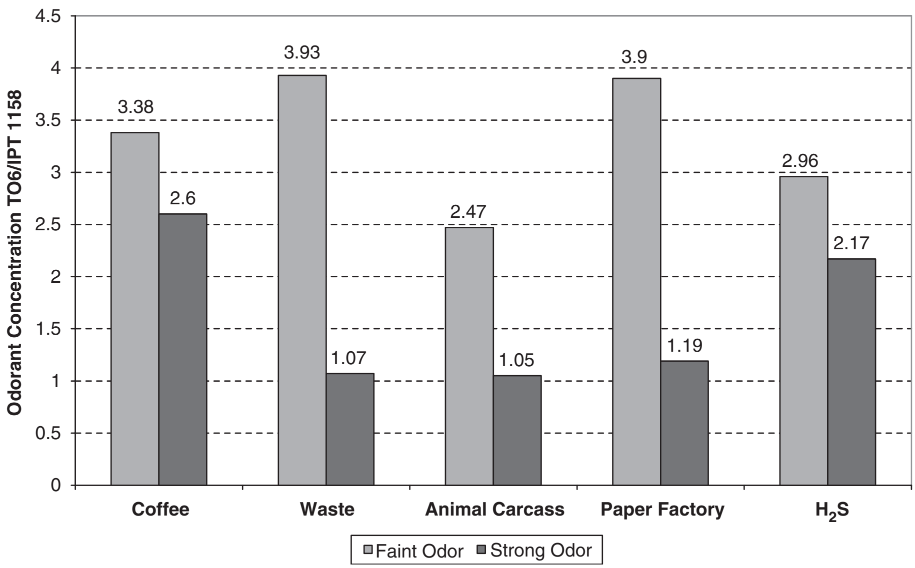

Fig. 11.8. Ratio of odorant concentrations by olfactometers TO6 and IPT 1158, faint and strong odors (after Habenicht, 1992).

Table 11.10. Comparative tests of odorant concentrations taken on two different days and at different times per day (after Habenicht, 1992)

Sample	First day		Second day	
	Morning	Afternoon	Morning	Afternoon
Sample 1	4800	5200	6300	5800
Parallel sample	4598	4096	7298	6889
Sample 2	13,777	12,274	11,585	14,596
Parallel sample	13,274	13,004	14,596	19,480

The number of possible influences on the olfactometric measurement makes it clear that in the future, quality assurance (QA) of odor measurement must rank higher than the attention paid previously. QA is important because the results of the measurements have an important bearing on approving the plant for operation.

11.5. Modular Types of Composting Systems and their Respective Odor Emissions

11.5.1. Composting Systems and their Modular Type Classification

Currently, there are approximately 420 composting plants in the Federal Republic of Germany, processing a total of about 8 million tons of material (Kehres, 2006). The numerous treatment methods within this large number of plants at present include 26 different composting systems (European Compost Network, 2006). The methods are subject to a nearly constant change of technology and manufacturers.

In order to simplify the discussion of the different systems below and to make them easier for the reader to understand, similar systems are combined in one group or one modular type. The composting systems currently available on the market have been classified into 6 types of modules, as shown in Table 11.11.

Simplifications within the various composting systems were made in their classification into modular types. These simplifications, however, did not change the flow chart of the individual system. So, for example, all processing steps that are necessary for the preparation of the biological material (e.g., metal separators, size reduction, screening, etc.) have been combined into one module as "pre-treatment." A similar approach has been followed for the block "fine preparation." In the following, the plant modules mentioned earlier are described in terms of general processing steps.

Box and Container Composting (Modular Type I)

Box and container composting systems are based on a very similar treatment system. The intensive decomposition of both systems is conducted in an enclosed room with forced

Table 11.11. Modular types for composting systems

Modular types	Composting system
Modular type I	Box and container composting
Modular type II	Channel and tunnel composting
Modular type III	Decomposition drums
Modular type IV	Windrow composting, aerated
Modular type V	Windrow composting, unaerated
Modular type VI	Special systems (composting in bricks, towers, and reactors)

aeration and complete collection of the exhaust gas. The capacities of the reactors are between 20 and 60 m^3.

In general, aeration of the reactors is carried out through perforated floors. The intensive stage of decomposition takes between 7 and 14 days, with the objective of maximizing the degradation of the material and simultaneously achieving hygienization. The advantage of this method is the complete monitoring of the decomposition parameters such as temperature, CO_2 and O_2 concentrations, and the control of the intensity of the aeration process and thus degradation. Another great advantage is the relatively simple collection of emissions. Thus, the odor emissions, especially at the beginning of the decomposition process, can be minimized.

Once the intensive decomposition period is finished, a decomposition degree of I to II can be assumed. In the event that the material requires a higher degree of decomposition, additional processing in a windrow or through the reactor must be performed.

Both systems are available with or without a re-stacker. The main difference between both systems is the transport of the material from the intensive decomposition phase to the subsequent decomposition phase. Concerning box composting, the material is placed in the box by means of a wheel loader or conveyor belt and transported by these means to subsequent decomposition processes. Container composting is carried out in such a way that after introducing the biowaste, the entire container is transported to the decomposition area by means of a crane or a truck and emptied again after the intensive decomposition process has been completed. A flowchart of modular type I is shown in Fig. 11.9.

Channel and Tunnel Composting (Modular Type II)

Channel systems have rows separated by fixed walls and with an open top, which are filled with biowaste for decomposition. Each row is aerated separately and re-stacked by a special re-stacker.

Tunnel composting is carried out in rows and the tops of the rows are closed; thus keeping the volume of exhaust air very low, which minimizes odor emissions during the first phase of decomposition, similar to box or container composting. Tunnels are offered with or without re-stackers.

Today, both methods are used for preliminary or main decomposition after which a subsequent stage of decomposition must be carried out to produce a mature compost. Some manufacturers are offering a tunnel system with which the total decomposition can be achieved in 7–11 weeks.

A flowchart showing modular type II is provided in Fig. 11.10.

Decomposition Drums (Modular Type III)

Decomposition drums are mainly used for mixed waste composting processes. The rotational motion of the drum mixes the material and homogenization, comminution, and aeration takes place simultaneously. The drum can only be used for preliminary or intensive composting. The time for pre-treatment lasts 1–7 days, depending on the type of plant. Drum systems with short detention times are meant for an optimal preparation of the material. Hygienization takes place during subsequent decomposition.

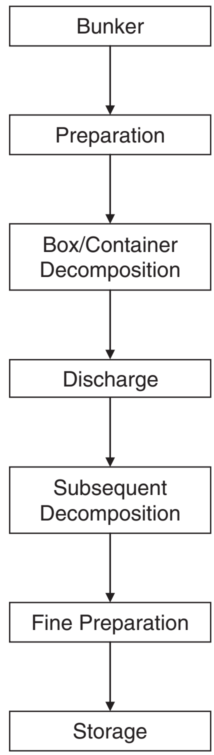

Fig. 11.9. Flowchart of modular type I (box and container composting).

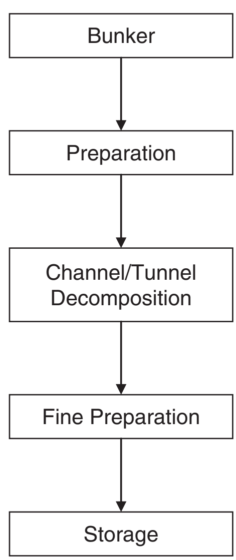

Fig. 11.10. Flowchart of modular type II (channel and tunnel composting).

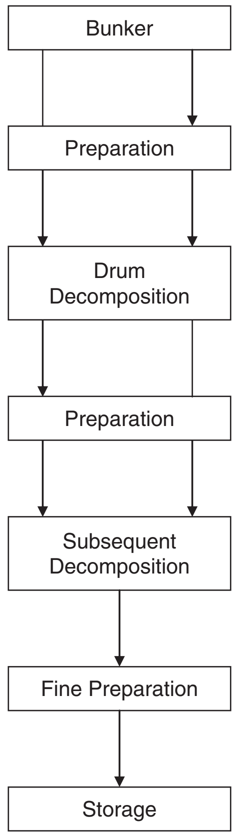

Fig. 11.11. Flowchart of modular type III (decomposition drums).

Fig. 11.11 shows the flowchart of a drum decomposition system. The two lines before and after decomposition are alternative lines as manufacturers offer both systems.

Aerated Windrow Composting (Modular Type IV)

Enclosed decomposition systems are usually used for dealing with potential odor problems through forced aeration and the reduction of decomposition areas at large input quantities, mostly in the form of table windrows. The windrows usually are re-stacked with a special automatic re-stacking device and are force-aerated (positive or negative aeration or a combination of both). In addition, water is added primarily during the re-stacking process. The level of aeration is usually controlled by monitoring the O_2 and CO_2 contents of the exhaust gas. The windrow height is about 3 m. According to the manufacturers, mature compost is ready within 8–12 weeks.

A flowchart of modular type IV is shown in Fig. 11.12.

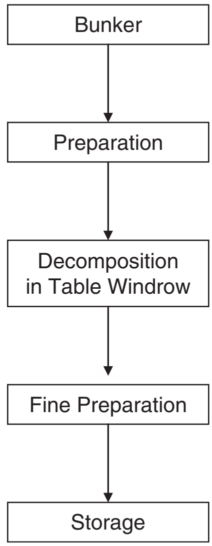

Fig. 11.12. Flowchart of modular type IV (windrow composting, aerated).

Unaerated Windrow Composting (Modular Type V)

The oldest and most simple form of composting is the unaerated windrow composting, usually in a pile that is not enclosed (open-air windrows), and is formed with biowaste and bulking material. For this purpose, a specific minimum volume is necessary so that the windrow does not cool down too rapidly. Windrows are naturally aerated. This natural aeration uses, in most cases, triangular windrows with a maximum height of 1.5 m, so that the oxygen supply of the microorganisms is assured. The re-stacking of the windrows is carried out by means of a wheel loader or a re-stacking machine. The re-stacking loosens the pile and during this process, the material is aerated as it comes in contact with the ambient air. Here, a maximum height of 1.5 m also makes sense. In cases where the windrows are higher (up to 3.0 m), aeration through a ground plate should be made. Due to the open construction and the generation of odors, aeration through the application of suction is recommended. The air removed from the pile must be discharged into a biofilter. The decomposition time lasts 3–6 months, depending on the re-stacking frequency. This method is mainly used with smaller input quantities under 6500 Mg/year.

A flowchart of modular type V is provided in Fig. 11.13.

Special Systems (Modular Type VI)

Two special methods are introduced here: “composting in stacked bricks” and “tower composting.” The “stacked brick” method is a special way of composting that is different from the usual composting methods. In this method, the material is compressed into bricks with a weight of up to 30 kg each, which are then stacked on pallets in the decomposition hall.

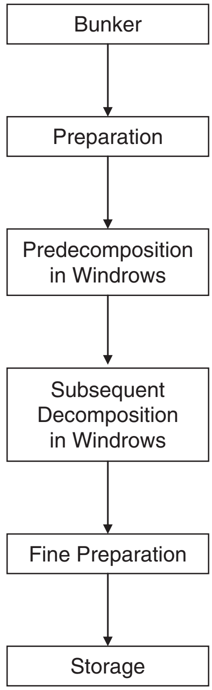

Fig. 11.13. Flowchart of modular type V (windrow composting, unaerated).

The bricks have a moisture content of approximately 55% (by weight). Because of the capillary effect, the bricks steadily dry out and aerobic decomposition processes are accelerated due to the simultaneous increase of temperature. Degradation is maintained over 4 weeks by watering measures. After this period, degradation comes to a stop and the material is preserved (Jäger and Emberger, 1995). For further treatment, the bricks must be crushed. This method results in fresh compost. Additional decomposition can take place after moisture is added to the material. According to statements made by the manufacturer, the decomposition period lasts from 5 to 6 weeks and reaches a decomposition degree of III to IV (Rethmann, 1994).

Tower composting can also be listed as a special method in the area of biowaste composting. However, up to now it has not been successful. As a rule, decomposition takes place in a main reactor and in another reactor for subsequent decomposition (tower). The material is introduced through a distributing device under the roof of the towers and is removed from the tower by a discharging screw. Re-stacking of the material takes place only during reloading of the material into the subsequent decomposition tower. Thereafter, the material can be moved in the reactor. The main decomposition time is 14 days, with an additional 28 days for subsequent decomposition.

Aeration of the material is carried out by forcing air through the ground plate. A flowchart of modular type VI is provided in Fig. 11.14.

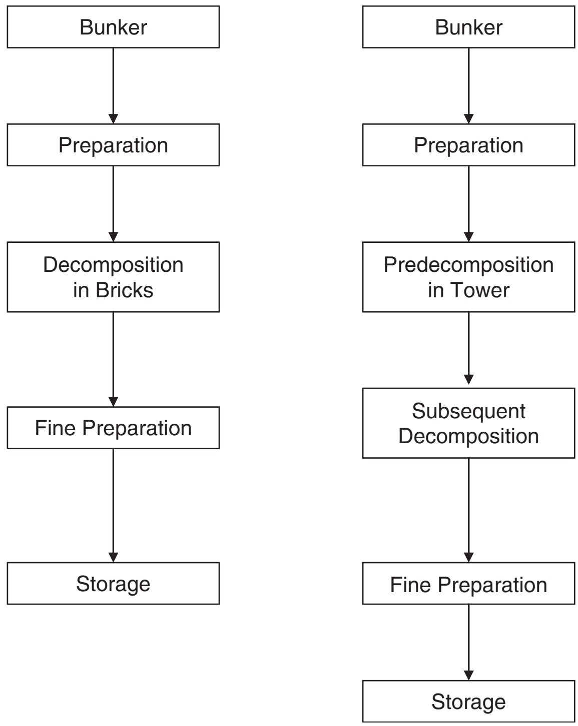

Fig. 11.14. Flowchart of modular type VI (special systems — left: brick; right: tower composting).

11.5.2. Odor Sources in Different Composting Systems

Nearly all steps of the composting process have to be considered as a source of odorous emissions. However, with increasing maturation of the material, the emissions heavily diminish. The partial steps of the process, and thus the emission sources, are divided into two levels within the dimensioning sheets. One level is the level of the generally valid process steps and the other level includes the specific process step. The main level is the modular type itself. The following plant modules are included in the generally valid process steps:

- delivery and bunker;
- preparation of fresh material;
- fine preparation;
- storage;
- biofilter; and
- diffuse sources.

The specific process steps are: a compound for re-stacking, watering, and aeration through the decomposition process. The decomposition process is divided into preliminary

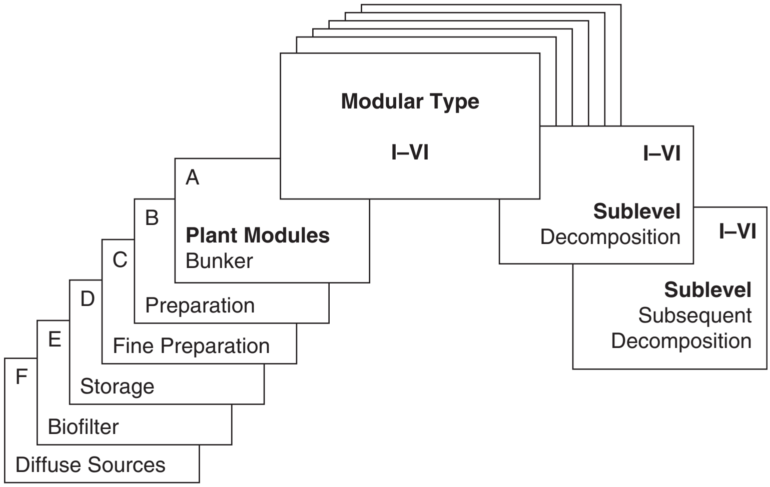

Fig. 11.15. Design of the different levels within the dimensioning sheets.

or intensive and subsequent decomposition. Fig. 11.15 shows the distribution of the various levels.

Fig. 11.16 shows the typical process steps of biowaste composting and the generated emissions related to air and water.

11.5.2.1. Generally Valid Process Steps

The term "generally valid process steps" means all the processing steps that are normally included in every composting plant. These are:

- delivery and bunker;
- treatment of fresh material;
- fine treatment;
- storage;
- biofilter; and
- diffuse sources.

This classification corresponds to the grouping in the concept of modular types that has been described in Section 11.5.2, Odor Sources in Different Composting Systems.

The odor emissions that are generated within these process steps are described later. The odorant concentrations listed in Tables 11.12–11.21 show the variations and the dimensions of the various measurements.

Delivery and Bunker

The various sections of in-vessel plants, such as the delivery and bunker areas, undergo forced aeration (air changes >1). The air removed from these sections is transported into

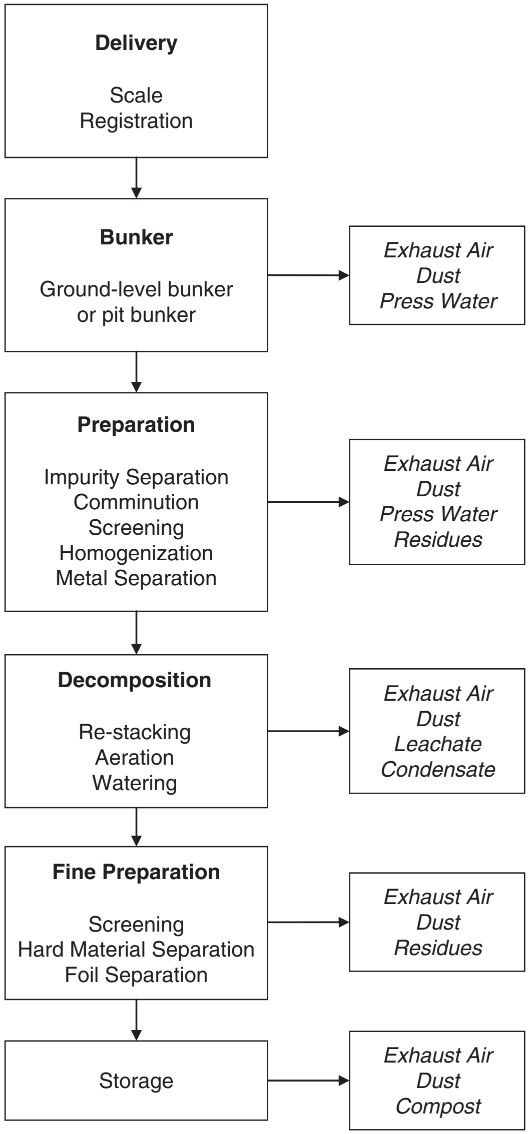

Fig. 11.16. Process of biowaste composting and odor-related emissions (Bidlingmaier and Müsken, 1992).

air treatment facilities (e.g., biofilter or biowasher) or injected into decomposition systems to reduce the volume.

According to Müsken and Bidlingmaier (1993), the specific air load (related to 1 m^3 of compost) of delivered fresh biowastes can be determined with 8.5–17 $OU/m^3 \cdot s$ with small plants (6500 Mg/year) and with 3.4–9.8 $OU/m^3 \cdot s$ with large plants (25,000 Mg/year).

According to Jager et al. (1993), the specific emission rates in the delivery area with 3−4 OU/m^3 · s, which are approximately of the same dimension as those measured in large plants. Köster (1996) indicates the emission rates related to the windrow surface with 2.9 OU/m^2 · s, a value similar to those given by Müsken and Bidlingmaier (1993) of 3.31−6.97 OU/m^2 · s.

Fig. 11.17 shows the odor radiation of freshly delivered biowaste over the year. This indicates that there is not only a relation between the composition of the wastes and the generated odorant concentrations but also a relation to the annual seasons and temperatures. Thus, the maximum odorant concentrations (>1000 to a maximum of 8500 OU/m^3) are generally measured between the months of May and September and the lower values (below 1000 OU/m^3) between October and April (Bidlingmaier and Müsken, 1992). Odorant concentrations from different measurements are listed in Table 11.12:

Preparation

The following individual steps can be considered as waste "preparation" in a compost plant:

- comminution;
- mixing and homogenization drum;
- screening;

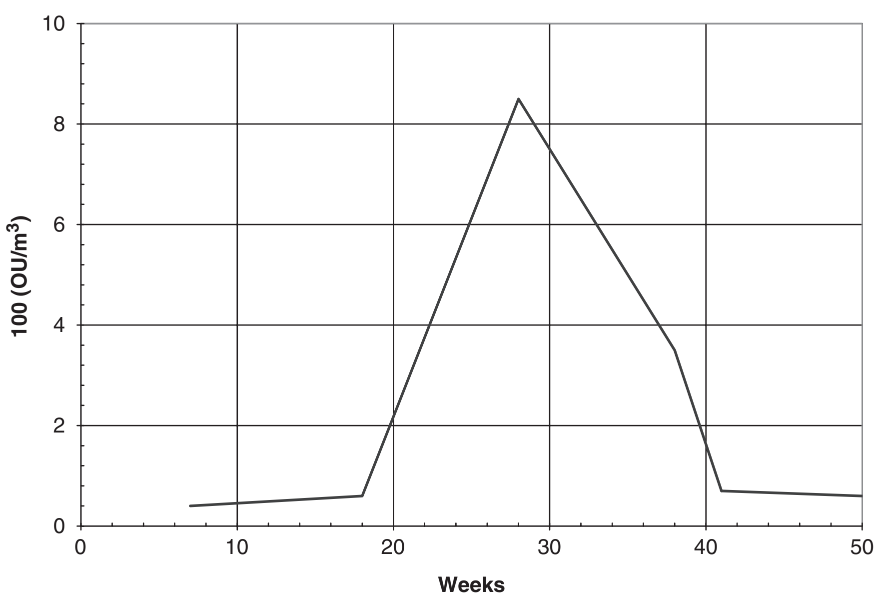

Fig. 11.17. Odor radiation from freshly delivered biowaste over the year (Bidlingmaier and Müsken, 1992).

Table 11.12. Odorant concentrations in the delivery and bunker area of a composting plant

Source	Odorant concentration (OU/m^3) Z50	Explanation
Leibinger and Müsken (1990)	3360–5470	Measured on the surface of the freshly delivered biowaste
	3070–8450	
	260–720	
Bidlingmaier and Müsken (1992)	630	
Eitner (1986)	250	Reception of household waste with exhaust air
Schade (1993)	200–400	8000 Mg/year throughput
	300–600	25,000 Mg/year throughput
	500	50,000 Mg/year throughput
Jager and Kuchta (1992)	200–800	Bunker and treatment
	500–800	50,000 Mg/year throughput
Fischer (1992)	100–300	–
Hensler and Schwarz (1995)	1900–2200	Bunker Reception box
	1000–4000	
Müsken (1989)	256–8450	Delivery biowaste
Müsken (1994)	100–300	Intake hall, 1-fold air exchange rate
	150–500	Pit bunker, green cuttings
	500–1000	Bush cuttings, comminuted
	1000–8500	Pit bunker biowaste, 2-fold air exchange rate
Bidlingmaier and Müsken (1991)	100–200	Delivery bush cuttings
	100–1000	Delivery biowaste
Bidlingmaier and Müsken (1992)	46–350	Pit bunker mixed waste
	7–73	Pit bunker biowaste
	150–8450	Flat bunker biowaste
Müsken and Bidlingmaier (1993)	46–350	Mixed waste
	ø 350; maximum 710	Biowaste, input 6500 Mg/year
	ø 180; maximum 510	Biowaste, input 25,000 Mg/year
Köster (1996)	80–400	Mixed waste
	300–12,300	Delivery biowaste
	290	Delivery of green waste

- magnetic separation; and
- manual separation.

Due to the potential for odor generation, the processing area of a plant is often planned in a hall together with the bunker area (see also Table 11.12). In new plants, the individual processing units (mills, sieves, conveyor belts) are installed such that they are completely enclosed and air can be removed from each processing unit separately. Only by this means, low number of air exchange rates can be achieved and the staff can work unmolested inside the hall. If all or most of the equipment in the processing area is enclosed, one can assume that at a low air exchange rate of >0.5, an odorant concentration of less than 200 OU/m^3 can be expected.

The material, as well as the air mass, will be moved one to three times, e.g., when the material is shredded, screened, or re-stacked. In measurements performed by the authors, samples were collected right after the windrows were formed. In smaller plants (6500 Mg/year), a mean value of 10 OU/m^3 · s (maximum 19 OU/m^3 · s) specific odorant loads were determined, whereas larger plants (25,000 Mg/year) showed 3.8 OU/m^3 · s (maximum 7.2 OU/m^3 · s). When the windrows are covered, specific odorant loads decreased with mean values of 2.6 OU/m^3 · s (maximum 5.0 OU/m^3 · s) were determined in small plants and in large plants 0.95 OU/m^3 · s (maximum 1.9 OU/m^3 · s).

In Table 11.13, odorant concentrations from different preparation ranges are presented from various sources in the literature.

Table 11.13. Odorant concentrations in the preparation of a composting plant

Source	Odorant concentration (OU/m^3) Z50	Explanation
Bidlingmaier and Müsken (1991)	200–1500	Enclosed shredder, feeding funnel and material feeding open
Bidlingmaier and Müsken (1994)	165	Machine hall mixed waste, Air exchange = 1.5
	17–48	Treatment hall, high air exchange rate
	185	Drum hall
	470	Grinding room
	2740–7100	Mixing drum, 14 days pre-degradation
	2810–9480	Discharge mixing drum, fresh material
Müsken and Bidlingmaier (1993)	5000 (maximum 9500)	Freshly treated material: uncovered
	1250 (maximum 2500)	Covered
Müsken (1994)	300–500	Exhaust air treatment hall
	1200–3000	Pre-comminution
	250–1200	Discharge screen
Eitner (1986)	185–600	Exhaust air from the hall
Leibinger and Müsken (1990)	2810–9480	Mix and homogenization drum (discharge after 1 day)
	2740–7100	(Discharge after 12–14 days)
Fischer (1992)	50–500	Sorting and separation area
Schade (1993)	200–500	Delivery and preparation
Anonymous (1994d)	407–1468	Indoor air, aerated
Hensler and Schwarz (1995)	2900	Screening drum
	370–840	Sorting room

Table 11.14. Odorant concentrations in fine preparation/refining of a composting plant

Source	Odorant concentration (OU/m^3) Z50	Explanation
Bidlingmaier and Müsken (1991)	200–600	Screening
Bidlingmaier and Müsken (1992)	21–57	Input screen, 70 days
	395	Output comminution, 73 days
	395	Output screen
	60	Biowastes
		Output screen, green wastes
Müsken and Bidlingmaier (1993)	<500	–
Müsken (1994)	1200	Screening
	300	Bagging, MC $<$ 35%
	600	Exhaust air screen + bagging
Eitner (1986)	85–300	–
Anonymous (1994d)	871	Hall air, wheel loader operation
Hensler and Schwarz (1995)	323–1773	Hall air
	1367–2580	Wheel loader operation

Refining

Very few odor measurements are available for the refining process, i.e., the preparation of the decomposed material for use (screening and bagging). In this case, mean values of about 500 OU/m^3 can be assumed. In the event that the screening station is enclosed, the values are distinctly below 100 OU/m^3. These values can be assumed if preliminary decomposition took place under optimal conditions, thus producing a mature compost. The results of some measurements made at the fine preparation/refining of composting plants are presented in Table 11.14.

Storage Area

Normally only a small amount of annoying odor is generated from compost storage when it can be assumed that the material is mature. Odorant concentrations of less than 100 OU/m^3 arise from the surface of compost that is at least 10-weeks old. Maximum values from windrows that were opened may increase to 1100 OU/m^3, but usually arise only where anaerobic pockets are formed or when incompletely degraded material is stored. Odorant concentrations in the storage area of composting plants are shown in Table 11.15.

Biofilter

Odor emissions from a biofilter consist of its own typical smell and the efficiency of removal of odors from the gas that is passed through the filter media.

According to measurements by Kuchta (1994), the efficiency of the different filters is between 30 and 85%. The low values of these measurements could be explained by

Table 11.15. Odorant concentrations in the storage area of a composting plant

Source	Odorant concentrations (OU/m^3) Z50	Explanation
Anonymous (1986b)	136–160	Enclosed, freshly cut up
Bidlingmaier and Müsken (1991)	50–300	Storage windrow
Bidlingmaier and Müsken (1992)	16–93	Storage windrow, undisturbed, 70 days
	85–310	Storage windrow, 112 days
	85–1,085	Storage windrow cut up, 70–150 days
Müsken and Bidlingmaier (1993)	80 (maximum 200)	Storage windrow, static
	250 (maximum 1100)	Storage windrow, cut up
Eitner (1986)	10–30	Open-air storage
Leibinger and Müsken (1990)	16–93	Static
	85–939	Cut up
Fischer (1992)	20–200	–
Müsken (1991)	20–90	Storage windrow, cut up
Müsken (1994)	250	Table windrow, static
	1200	Table windrow, cut up
Anonymous (1994d)	203	Windrow static
Schade (1993)	150–300	–

improper installation of the filter and/or by improper maintenance (which could be proved). Adequate measurement technology and proper maintenance yield an efficiency of up to 95% (Kuchta, 1994).

According to the state-of-the-art, a maximum odorant concentration of 100–150 OU/m^3 can be assumed on the output side in a properly maintained filter.

Output concentrations of different plants are listed in Table 11.16.

The diffuse sources of odor in a composting plant are:

- emissions from open hall gates;
- dirt on traffic areas;
- delivery traffic, odors from waste collection vehicles;
- shipping of compost; and
- open containers with impurities.

To cover an emission prognosis, Kuchta (1994) proposes an additional charge of 10% of the calculated emissions. According to Table 11.17, odorant concentrations of 20–200 OU/m^3 can be expected, which can be mostly explained by dirty traffic areas.

Only a few evaluations about diffuse sources are available. Table 11.17 shows some results.

Table 11.16. Odorant concentrations at the biofilter of composting plants

Source	Odorant concentrations (OU/m^3) Z50	Explanation
Anonymous (1993b)	336–977	Input biofilter
	93–163	Output biofilter
Anonymous (1993b)	2000	Crude gas, at turning
	100	Clean gas, at turning
	1300	Crude gas, static
	84	Clean gas, static
Anonymous (1994b)	10–88	Output biofilter
Anonymous (1994c)	772–1396	Crude gas
	60–106	Clean gas
Fischer (1989)	100–287	–
Fischer (1991a)	373	Crude gas filter, at night
	39	Clean gas filter, at night
	129–313	Crude gas filter, during the day
	16–44	Clean gas filter, during the day
Fischer (1992)	50–250	–

Table 11.17. Odorant concentrations of diffuse sources in a composting plant

Source	Odorant concentrations (OU/m^3) Z50	Explanation
Bidlingmaier and Müsken (1991)	50–200	Traffic areas
Fischer (1992)	20–200	Traffic areas
Müsken (1994)	50–200	Traffic areas

11.5.2.2. Specific Process Steps in Different Modular Types

The decomposition system of modular types belongs to the specific process steps. The results of odor measurements in different plants are presented and explained in the following paragraphs.

Modular Type I — Box and Container Composting

The data in Table 11.18 show the results of odor measurements in bioreactors. It is obvious that the water content of the decomposition material, and thus its biological activity and temperature, has a decisive influence on the odor emissions when they escape from

Table 11.18. Odorant concentrations at boxes and containers

Source	Odorant concentration (OU/m^3) Z50	Explanation
Leibinger and Müsken (1990)		Subsequent decomposition in open land windrows after 1 week in the reactor
	11,300	Piling the windrow before
	85–240	Turning, 2–8 weeks
	970–3820	After turning, 2–5 weeks
	350–460	After turning, 7–8 weeks
Müsken (1991)		Cut up material
	360–1220	7 days, dry
	11,300–15,900	7 days, humid
	2740	14 days, dry-humid
	15,940–17,400	Crude gas exhaust air, 7 days, humid
Bartsch and Wiegel (1988)		*1-day old*
	10,109	Before cooler
	4230–5295	Biofilter input
	337	Indoor air
		2-day old
	8932	Before cooler
	4266–4861	Biofilter input
	337	Indoor air
		6-day old
	289	Before cooler
	171–193	Biofilter input
	254	Indoor air
		7-day old
	176	Before cooler
	110–156	Biofilter input
	81	Indoor air
Wiegel (1989)		Subsequent decomposition, surface, 1–6 weeks after reactor
	178–270	Static
	270–348	Cut up
Itu (1992)	49–221	Measured at the filter outlet of the box
Schade (1993)	25,000–30,000	7-day old, $5\,m^3/m^3 \cdot h$
	10,000–13,000	5-day old, $10\,m^3/m^3 \cdot h$
	10,000	1-day old, $20\,m^3/m^3 \cdot h$
	200	7-day old, $20\,m^3/m^3 \cdot h$
Bidlingmaier and Müsken (1992)		*Output*
	120–1220	7 days, dry (MC = 30–40%)
	11,300–15,900	7 days, moist (MC = 50–60%)
	2740	14 days, dry-moist (MC = 40–50%)
		Exhaust air before heat exchanger
	10,110	1 day
	8930	2 days
	290	6 days

Table 11.18. Odorant concentrations at boxes and containers — *Cont'd*

Source	Odorant concentration (OU/m^3) Z50	Explanation
	180	7 days
	15,940–17,400	7 days, moist
		Subsequent decomposition, MC < 40%, unaerated piled windrow, 1 week in box
	11–340	Static
	140–350	Cut up
Müsken and Bidlingmaier (1993)	30,000	$5\,m^3/m^3 \cdot h$ fresh air, 7 days, moist
	200–10,000	$20\,m^3/m^3 \cdot h$ fresh air, 7 days
	13,300	Output, 7 days, moist

the reactor. The special advantage of this system, odor minimization through enclosed reactors, will be achieved only if an additional degradation process is conducted; moisture is not added after a period of 14 days. If moisture were to be added after the 14-day period, it would lead to renewed biological activity and, more than likely, renewed odor generation.

A mean value of approximately $0.6\,OU/m^2 \cdot s$ can be used for a dry (MC = 30–40%) and freshly discharged compost. If the material is moist, up to $11\,OU/m^2 \cdot s$ can be assumed. This is equivalent to the amount of odor radiation of freshly re-stacked biowaste after 1 week of degradation on a triangular windrow.

The odorant concentrations in the exhaust air from a bioreactor must be assumed at about $17{,}000\,OU/m^3$ whereby the air, which is forced in, is significant. Large amounts of air cause a substantial reduction in the odor concentrations. Odor concentrations can be as low as $200\,OU/m^3$, primarily toward the end of the preliminary decomposition phase at a simultaneously low moisture content (35%).

Measurement of pre-degraded biowastes from boxes and containers are available for the subsequent stage of decomposition. The measurements were obtained from a dry, stabilized material (moisture content <40%). The pre-degraded material was piled on a windrow without aeration. The windrow was not re-stacked and moisture was not added. Odorant concentrations between 50 and $270\,OU/m^3$ were measured on the surface of static windrows that were about 8 weeks old. This means a maximum odor radiation of about $1.2\,OU/m^2 \cdot s$ from the surface of the windrow. If the windrows are opened, values between 140 and $340\,OU/m^3$ are achieved. That is a maximum surface radiation of $1.6\,OU/m^2 \cdot s$. The mean values of the concentrations for open windrows are about $80\,OU/m^3$ higher than those of static windrows.

Modular Type II — Channel and Tunnel Composting

At present, no odor data are available for tunnel and channel composting. Therefore, the odor data of modular type I (box and container composting) can be used due to many similar features of the processes.

The similar features primarily are the following: the degradation in the reactors is used as preliminary decomposition, thus the detention time of both modular types are nearly equal. As a rule, a detention time of 1–2 weeks can be considered.

The difference from tunnel composting is associated with the way the material is moved in the reactor. In most of the tunnel and channel systems, the material is continuously moved from the inlet to the outlet. In the box or container composting, the material rests in the same place within the reactor and, in some cases, is moved by means of a mechanism at the bottom of the reactors. During the first 2 weeks of decomposition, the following presumptions are not valid for the systems of modular type II, which remain in the tunnel or in the channel the entire time.

Odorant concentrations obtained from box and container composting units are listed in Table 11.19. Special data referring to modular type I have not been considered.

Table 11.19. Odorant concentrations at tunnel and channel composting, following the data of box and container composting

Source	Odorant concentration (OU/m^3) Z50	Explanation
Leibinger and Müsken (1990)		Subsequent decomposition for the system in open land windrows after 1 week in the reactor
	11,300	Piling of the windrow
	85–240	Before re-stacking, 2–8 weeks
	970–3820	After re-stacking, 2–5 weeks
	350–460	After re-stacking, 7–8 weeks
Müsken (1991)		Cut up material
	360–1220	7 days, dry
	11,300–15,900	7 days, humid
	2740	14 days, dry humid
	15,940–17,400	Crude gas exhaust air, 7 days, humid
Wiegel (1989)		Subsequent decomposition, surface, 1–6 weeks after reactor
	178–270	Static
	270–348	Cut up
Itu (1992)	49–221	Measured at the filter outlet of the box
Bidlingmaier and Müsken (1992)		Discharge
	120–1220	7 days, dry (WC = 30–40%)
	11,300–15,900	7 days, humid (WC = 50–60%)
	2740	14 days, dry-humid (WC = 40–50%)
		Subsequent decomposition, WC < 40%, unaerated
		Piled windrow, 1 week in box
	11–340	Static
	140–350	Cut up

Modular Type III — Decomposition Drums

The data in Table 11.20 show the odorant concentrations of some measurements of odorant modular type III emissions in decomposition drums and the subsequent decomposition.

As a rule, the detention time in the decomposition drum fluctuates between 1 and 3 days. Very few systems provide a detention time of up to 7 days. The discharge from a decomposition drum, used as preliminary decomposition device, is deposited in an enclosed hall,

Table 11.20. Odorant concentration at decomposition drums

Source	Odorant concentration (OU/m^3) Z50	Explanation
Eitner (1986)	600	–
Fischer (1991a)	362	Drum static, compost surface
	102–645	5 min revolve
	479–575	10 min revolve
	313–627	15 min revolve
	249–406	Fresh discharge
	271–497	Subsequent decomposition, 7 days
	222–296	Subsequent decomposition, 14 days, re-stacked once
Leibinger and Müsken (1990)	2800–9500	Output, 1 day, moist
Bidlingmaier and Müsken (1992)		
	11,600	Output, 7 days, moist
	7100	Output, 12 days, moist
	2750–6900	Output, 14 days, moist-dry
	14,600	Crude gas exhaust air, 1 day, moist
	15,500	Crude gas exhaust air, 4 days, moist
	23,900	Crude gas exhaust air, 5 days, moist
	27,600	Crude gas exhaust air, 6 days, moist
		Subsequent decomposition in open air windrows after 1 week revolving drum
	11,590	Piling of the windrow
	220–500	Static, 7–14 days
	210–790	Before re-stacking, 2–3 weeks
	30–90	Before re-stacking, 5–8 weeks
	230–4320	After re-stacking, 2–8 weeks
Fischer (1992)	20,000–80,000	–
Schade (1993)	18,000	8000 Mg/year, exhaust air amount 600 m^3/h
	30,000	60,000 Mg/year
Müsken and Bidlingmaier (1993)	15,000	6500 Mg/year, 2.5 days, fresh air 5 $m^3/m^3 \cdot h$
	30,000	25,000 Mg/year, 1.5 days, fresh air 5 $m^3/m^3 \cdot h$

so the exhaust air can be removed under controlled conditions and transported into an air purification system.

If the odorant concentrations in the inner part of a drum are considered, depending on the type of measurement (see Table 11.20), very different values are achieved.

Despite the different aeration rates (2.4–20 m^3 of air per m^3 of composting material), concentrations in the tight variation range of 10,000–35,000 OU/m^3 could be measured. At these measurements, samples were taken from drums with a detention time of 1.5 days.

Odor loads of 40,000–50,000 OU/s were measured in the drum exhaust air at air volumes of mostly over 15–20 m^3 of air per m^3 of compost material per hour and at a calculated drum content of approximately 330 m^3 of compost. Values of 120–150 OU/$m^3 \cdot s$ were calculated from the processed compost volume.

If the drum is used as a real "decomposition drum" with detention times of 7 days, a distinct increase of the odorant concentrations is shown in the exhaust air over the time base. After 7 days of decomposition, the discharge material shows values of about 10 OU/$m^2 \cdot s$. Moist, raw material from decomposition boxes and unaerated triangular windrows that have been newly re-stacked have the same values after one week of decomposition. According to Schade (1993), similar odorant concentrations could be determined and are in the range of 18,000–30,000 OU/m^3.

The results from Eitner (1986) proved to be too old (Section 11.5.2, Odor Sources in Different Composting Systems) and thus classified as being too low. However, in order to illustrate the difference, Eitner's results have been included in all of the tables. It could not be explained why the values of Fischer (1991a,b) were so low. Just like the other results in the table show, by far higher values, these higher concentrations are the basis in the following sections.

Modular Type IV — Windrow Composting, Aerated

The data in Table 11.21 show odorant concentrations from different plants using aerated windrow composting.

Aerated windrow composting is classified into windrows aerated by positive and negative pressure. According to the state-of-the-art, windrow composting using forced aeration is mainly carried out with a completely enclosed table windrow. However, even today there are still open–air windrows or windrows under roofs that are aerated. Because of the odor generation, aeration by means of negative pressure is preferable in this type of composting method.

As shown in Fig. 11.18, forced aerated windrows demonstrate a decreasing odor emission with an increase in the age of the compost. This statement can be transferred to other decomposition procedures by using mean values from up to 4 single measurements (Bidlingmaier and Müsken, 1992).

In their tests, Bidlingmaier and Müsken (1992) determined that concentrations on the surface of the windrow decreased by a factor 10 from the first to the tenth week of decomposition. However, this could not be determined in all composting plants, but the trend could be ascertained in all plants.

Table 11.21. Odorant concentrations at aerated windrow composting

Source	Odorant concentration (OU/m^3) Z50	Explanation
Fischer (1989)	1500–4100	Hall suction
	1370–14,600	Decomposition hall, decreasing with decomposition age
Anonymous (1993b)		Table windrow
	1900–2100	Crude gas, at re-stacking
	73–150	Clean gas, at re-stacking
	1200–1500	Crude gas, static
	69–275	Clean gas, static
	660–2300	Decomposition hall
	110	Subsequent decomposition
Anonymous (1993c)		Table windrow
	5793	Crude gas, at re-stacking
	362	Clean gas, at re-stacking
	3469	Crude gas, static
	342	Clean gas, static
	10,321	Crude gas, direct on windrow
Anonymous (1994b)		Table windrow
	811–2423	Crude gas, at re-stacking
	70–224	Clean gas, at re-stacking
	772–1396	Crude gas, static
	60–106	Clean gas, static
Jager and Kuchta (1992)	1000–12,000	Windrow exhaust air, suction aerated
	1400–1600	Subsequent decomposition, pressure aerated
	280–320	Subsequent decomposition, pressure aerated, after 4–5-fold dilution
Schade (1993)	1000–10,000	Windrow exhaust air, suction aerated
		Hall exhaust air after seventh week decomposition, pressure aerated, $h = 2$ m,
Müsken (1991)	300–400	After 4–5-fold dilution
		Triangular windrow, pressure aerated, not prepared, 0–6 weeks
	7810	At piling
	50–420	Before re-stacking
	160–10,030	After re-stacking
Bidlingmaier and Müsken (1991)		Table windrow with green waste
	100–300	Pre-decomposition, suction- or pressure-aerated
	500–2000	Pre-decomposition, at re-stacking
	100–150	Subsequent decomposition (>3 month), suction- or pressure-aerated
	200–500	Subsequent decomposition (>3 month), at re-stacking

(*continued*)

Table 11.21. Odorant concentrations at aerated windrow composting — *Cont'd*

Source	Odorant concentration (OU/m^3) Z50	Explanation
Bidlingmaier and Müsken (1992)		*Table windrow, surface, pressure aerated*
	2460–14,600	Maximum 7 days
	18,300	Maximum 10 days
	25,900	Maximum 31 days
	1240	Maximum 70 days
	345	Maximum 77 days
		Pile, surface, pressure aerated
	47,730–56,070	1 day, fresh piled
	100–15,440	Static t, 5–42 days, decreasing
	10,650–76,930	1 day after re-stacking, decreasing
		Table windrow, hall exhaust air, pressure aerated
	1150–5020	0–70 days
	22,600–31,200	At re-stacking
	2470–4610	After re-stacking
		Mixed waste, table windrow, surface, suction aerated
	30–1900	Hall exhaust air
	363–20,200	Windrow exhaust air
	9–4300	Windrow surface
Müsken and Bidlingmaier (1993)		*Table windrow, suction aerated*
		$h = 2.30$ m
		0–70 days
	350–4300	Surface
	11,500–20,000	Windrow exhaust air, 19,800 m^3/h
	<2000	Hall exhaust air, full capacity
		Table windrow, pressure aerated
		0–70 days
	8000	Static (fresh air 19.800 m^3/h)
	30,000	20% fresh re-stacked
	5000/30,000	Hall exhaust air, with/without re-stacking
Müsken (1994)		*Table windrow*
	300–800	Suction aerated, surface
	1500–4500	Suction aerated, surface, at re-stacking
	500–3000	Pressure aerated, surface
	1200–5000	Pressure aerated, surface, at re-stacking
	580–2240	Hall exhaust air
		Table windrow as filter, after 16 weeks
	250	Active filter element
	800	Adapted filter element
	1200	Piling/cut up

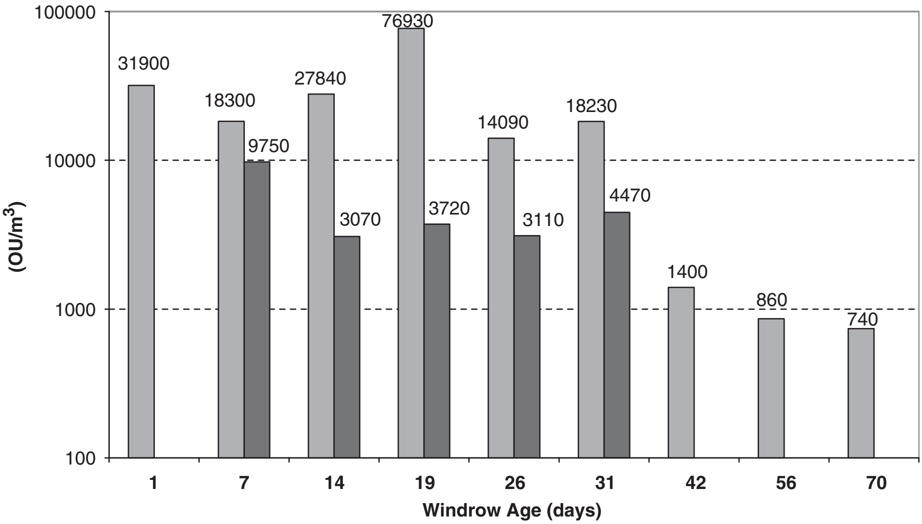

Fig. 11.18. Odorant concentrations on the surface of forced-aerated windrows.

The results of the tests showed that, on the surface of static windrows aerated by positive pressure, during the first week of decomposition odor concentrations of 10,000 OU/m^3 with peaks of up to 15,000 OU/m^3 can be expected, and up until the fifth week with odorant concentrations of about 5000 OU/m^3. After this time, the values decrease distinctly to less than 2000 OU/m^3. Values of up to 30,000 OU/m^3 were measured after re-stacking with distinctly higher peaks in the fourth and fifth weeks of decomposition. A decreasing trend was detected after this period. With respect to the processed compost, volume-specific loads of 12–45 OU/m^3 $\cdot$ s can be calculated for the first 5 weeks of decomposition after the re-stacking processes.

After the assessment of all measurements, mean values of 8000 OU/m^3 for static windrows and 30,000 OU/m^3 for newly re-stacked windrows could be ascertained at a model plant with a throughput of 25,000 Mg/year. Similar values were obtained in the work conducted by Jager and Kuchta (1992); they indicate values between 1000 and 12,000 OU/m^3 according to the decomposition age of the aerated windrows.

Compared with triangular windrows that are not aerated and with those windrows using forced aeration, essentially lower odorant concentrations are measured in windrows aerated by negative pressure. Windrows aerated through negative pressure are often used in the open air and the discharged air is forced through subsequent decomposition windrows. These windrows are effectively used as filters and, at the same time, moisture is added.

There is also a relationship between the age of the compost and the odorant concentration in windrows aerated by suction. The measurements were carried out at composting plants that process mixed waste, which, regarding odor emissions, behave in a similar way as biowaste plants. A mean concentration of 1000 OU/m^3 was measured with material that is 10 days old and up to 88 OU/m^3 with material that was approximately 65 days old. The difference between static windrows and newly re-stacked windrows is not so distinct as with windrows that are not aerated and those that are forced aerated.

Referring to a model plant with a throughput of 25,000 Mg/year, Bidlingmaier and Müsken (1992) assume a mean value of 350 OU/m^3 and peak values of up to 4300 OU/m^3 at the surface of windrows aerated by suction. Measurements of the exhaust air from the windrow reached mean values of 11,500 OU/m^3 and maximum values of up to 20,000 OU/m^3.

Similar values as those obtained by Bidlingmaier and Müsken (1992) were measured by Köster (1996). Considering the odorant flow on top of the windrows related to 1 m^2, Köster detected 760 OU/m^2 · h, however, lower by approximately 300 OU/m^2 · h. Köster explained this difference by the effect of the membrane with which the windrows were covered in the plants researched.

Modular Type V — Windrow Composting, Unaerated

Unaerated windrows are mostly used in small, decentralized plants and are not enclosed — modular type V. The odor emissions are directly discharged into the atmosphere.

The odorant concentrations of unaerated windrows can also be considered to decrease as the degradation process evolves. Furthermore, extreme differences between static windrows and newly re-stacked windrows can be recognized with unaerated windrows. The differences are, by far, more significant than with aerated windrows. Fig. 11.19 shows this relationship. Results of some measurement of different forms of windrows and material ages are listed in Table 11.22.

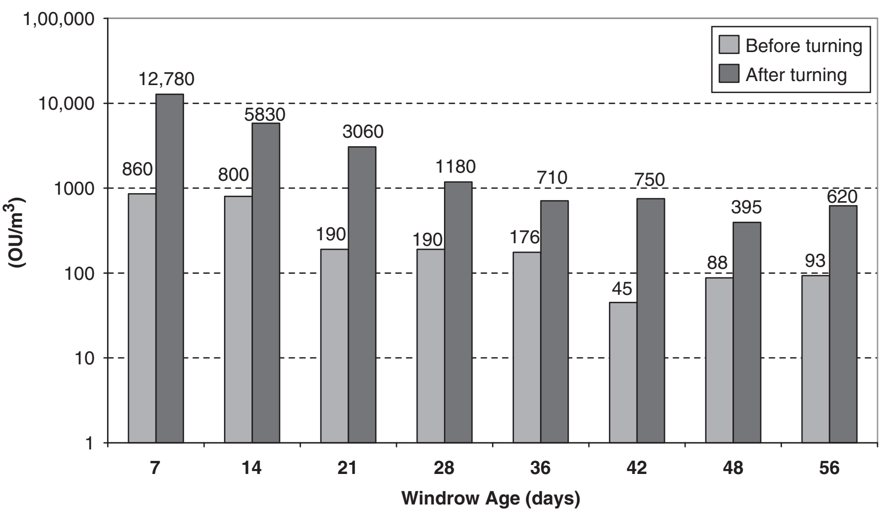

Fig. 11.19. Odor radiation from unaerated triangular windrows of biowaste (example) (Bidlingmaier and Müsken, 1994).

Table 11.22. Odorant concentrations at unaerated windrow composting

Source	Odorant concentration (OU/m^3) Z50	Explanation
Fricke et al. (1989)		Pre-decomposition, maximum 3-weeks old
		Freshly piled
	3494–6419	Freshly piled, covered
	57–2308	Static, 1 day
	5565–6297	Static, 1–2 weeks
	1154–4321	Static, 3 weeks
	76–393	Static, covered, 1 week
	3255	Static, covered, 2–3 weeks
	63–348	
	34–134	Subsequent decomposition
Köster (1996)		*Triangular windrows, static*
	800–7600	Up to 2 weeks
	140–680	2–8 weeks
	40–205	8–13 weeks
		Triangular windrows, after re-stacking
	10,000–20,000	Up to 2 weeks
	1000–6300	2–8 weeks
	40–205	8–13 weeks
Müsken (1991)		*Triangular windrow, 1 week pre-decomposition in reactor*
	11,300	At piling
	85–190	Before re-stacking
	350–3820	After re-stacking
		Triangular windrow, 1 week pre-decomposition in decomposition drum
	11,590	At piling
	30–790	Before re-stacking
	230–4320	After re-stacking
		Triangular windrow, without pre-decomposition
	4420–5280	At piling
	860	Freshly piled, covered
	30–8210	Before re-stacking
	345–14,820	After re-stacking
Müsken and Bidlingmaier (1994)		*Triangular windrows, surface*
	5570–6300	After piling, 1 day
	76–5590	6–21 days, static
	34–130	22–112 days, static
	710–1150	7 days, before re-stacking, covered
	8210	7 days, before re-stacking, not covered
	17–2040	14–56 days, before re-stacking

(*continued*)

Table 11.22. Odorant concentrations at unaerated windrow composting — *Cont'd*

Source	Odorant concentration (OU/m^3) Z50	Explanation
	420–16,870	6–21 days, after re-stacking
	160–2590	22–56 days, after re-stacking
		Table windrow, surface
	1900–48,400	7–21 days
	160–9170	28–98 days

At the beginning of the decomposition process, the odorant flows related to the surface are in the range of 10.5 $OU/m^2 \cdot s$. This corresponds to radiations from equally aged, moist discharge material from decomposition drums and decomposition boxes. After 14 days, the value lowers to one-half (4.8 $OU/m^2 \cdot s$), after 3 weeks to one-third (2.5 $OU/m^2 \cdot s$), and after 4 weeks a mean value of about 10% of the initial value was measured.

Köster (1996) measured area-related values of 21,600 $OU/m^2 \cdot h$ (related to 1 h), which correspond to a converted value of 6.0 $OU/m^2 \cdot s$ in a static windrow, at a maximum of 2 weeks old. Köster quoted values of 43,200 $OU/m^2 \cdot h$ (12 $OU/m^2 \cdot s$) measured in freshly re-stacked windrows. Thus, he achieved similar results as those obtained by Bidlingmaier and Müsken (1992). After 1 week of decomposition, related to the volume of triangular windrows, a value of 27 $OU/m^3 \cdot s$ can be considered after re-stacking at odorant concentrations of 13,300 OU/m^3. After 3 weeks, the value decreased to 6.3 $OU/m^3 \cdot s$; if decomposition has reached degree III, the specific load is only 1.2 $OU/m^3 \cdot s$. The values for static windrows are very low. A specific load of 2.0 $OU/m^3 \cdot s$ can be considered until the second decomposition week and older windrows have values of approximately 0.4 $OU/m^3 \cdot s$. The rather rare unaerated table windrows have essentially higher odorant concentrations than the triangular windrows. The values can be compared with those of forced-aerated table windrows. The resulting odor loads, however, are definitely lower, as the airflow is caused exclusively by the thermal current of the windrows.

Modular Type VI — Special Methods

Composting in bricks has heavy odor emissions only at the beginning of decomposition, as the material is progressively drying out to a moisture content of 30–35%. The compressed material, stacked on pallets for 5–6 weeks in the form of bricks, is stored in the same place in a decomposition hall. It is not re-stacked and is not forced aerated. With other methods, high odor emissions would arise, but this system can be looked upon as being advantageous. Addition of moisture to the material for subsequent decomposition would result in considerable odor emissions. With a decomposition process that is not optimal, odor emissions arise after decomposition due to the break up of the bricks in the mill and the following screening processes. Odorant concentrations at the special process with bricks are given in Table 11.23.

Table 11.23. Odorant concentrations at the special process with bricks

Source	Odorant concentration (OU/m^3) Z50	Explanation
Bidlingmaier and Müsken (1992)	14,700	Fresh bricks
	101	Old bricks
Bidlingmaier and Müsken (1992)	60–165	Hall air, 0–30 days
	14,700	Mixed waste, 7 days, surface
	100	Mixed waste, maximum 30 days, surface

At the completion of this evaluation, no data were available for the system of tower composting. This special method cannot be compared with any other system. It is necessary to supplement the dimensioning sheets with these data in the next years.

Within the modular type "special systems," it is just the main level described in Annex A for both composting methods because available data were too fragmented or not available at all.

11.6. Air Ventilation in Composting Plants

The possible features of air ventilation in the internal plant, described in this section, are mainly based on the specifications presented elsewhere in this chapter. The target for an optimized air management system in a composting plant is to minimize the emitted odorant mass flow (air load or source concentration) measured in Odor Unit/hour or in Odor Unit/second. For this purpose, different instruments are available according to plant technology and plant size.

The intelligent distribution of the air volumes produced in partly enclosed or totally enclosed plants is of highest importance, but measurements for a reduction of odor emissions can also be conducted in open composting plants.

In order to take the correct individual steps, knowledge of the following parameters is required:

- **Quality of the exhaust air** of the individual components of the plant and their respective unit processes. In addition to the odor load, it is also important to know the relative humidity of the air, the dust content, other compounds in the air (e.g., ammonia, organic acids, etc.), and, in the case of working places, the bacterial concentration. The actual conditions of the plant and the season can also play a part.
- **Exhaust air volume** from the individual sections of the plant and their respective unit processes. The volume of exhaust air can vary substantially, depending upon the conditions of the plant or of the plant components (e.g., day and night operation, maintenance, etc.).
- **Fresh air demand** and necessary quality of fresh air in those sections of the plant or plant units that are designed for multiple use of air streams. So, for example, the fresh

air for windrows in forced aerated windrows can be of very poor quality; however, the necessary air volume strongly depends on the decomposition process and is of little importance. Fresh air of lower quality can be forced into enclosed decomposition halls (without working places) after adequate dust removal. Buildings with equipment (coarse and fine treatment) are only partially suitable to receive used airflows.

Concerning the multiple use of airflow, in general, quality graduations have to be considered, i.e., the exhaust airflow with a low odor load can be used as new air supply only in an environment with a high odor load. If the opposite were to be done, additional cleaning measurements would be necessary, which is contradictory to cost-effective plant management.

Planning of air management that is suitable for the individual plant configuration implies:

- a correct assessment of the concentration measurements for odorants, which is the basis for the load calculation,
- an assessment of the external effects of the selected composting method by means of an emission/immission prognosis,
- best attention given to the purification of the exhaust air and plant operation, and
- the setup of an internal plant concept to avoid odor emissions over the allowable amounts.

Assessment of Odor Measurements

The values for odorant concentrations that can be calculated for the different process parts of waste composting and which must be assessed in different ways can be classified into two main groups.

These are values that can be directly allocated to an airflow, such as exhaust gases from preliminary decomposition units or from decomposition halls (active odor sources). A direct calculation of odor loads can be carried out. Furthermore, these exhaust gases can be easily collected and supplied to a purification plant for deodorization.

The other main groups of measurement values are: the odor radiation from windrow surfaces or during delivery (passive odor sources). They cannot be allocated to a direct exhaust airflow; a load consideration is therefore not easily possible. For the determination of the odor load of these passive odor sources, only approximate values are available in the form of conversion factors that have been developed by the sample collection equipment. Considering this aspect, the achieved load values (in Odor Unit/$m^2 \cdot s$) for passive odor sources on areas can be applied only to compare dimensions; an exact calculation of, for example, the source intensity or the volume is not possible.

A last issue relevant to the assessment of odor data is the intensity of odor emissions that are to a great extent dependent on the temperature. Since the substances that cause an odor impression are volatile, the temperature of the odor source (e.g., the windrow) is of importance. Additionally odor-intensive inter-degradation products exist in their highest concentration during the first phase of degradation of the composting process.

Emission and Immission Prognosis

The assessment of the external effects of composting plants regarding their odor emissions (immission prognosis) makes a differentiation necessary in two cases:

- Systems working partially or totally without an enclosure need calculations of the intensity of the odor emissions for each part of the plant that is emitting the odors.
- Completely enclosed composting plants need only a calculation of the exhaust air volume for the determination of the source intensity; exhaust air cleaning according to the state-of-the-art is provided, as one can assume that constant odorant concentrations exist in the cleaned exhaust air which, regarding their amount, only are dependent on the purification process.

In the first case, which is relevant to smaller plants with an input of approximately 6000 Mg/year and a total decomposition time of 10 weeks, the odor loads shown in Table 11.24 can be taken as an example for a calculation. A rough comparison shows that a composting plant with a throughput of approximately 6000 Mg/year emits about 4200 OU/s at strictly windrow decomposition on triangular windrows that are not aerated ($h = 1.60\,\mathrm{m}$), in case of a weekly re-stacking until the third decomposition week and every 2 weeks until the tenth decomposition week. Measures to reduce emissions, such as covering of the windrows with shredded material or semi-permeable membranes (air-permeable canvas), have not been considered here.

The use of decomposition boxes in the first decomposition week reduces the total load by approximately 10%; if the detention time in the box is extended by 2 weeks, a reduction of 40% of the total load is achieved, under the condition that an optimal moisture content for the decomposition progress is adjusted. In this case, purification of the exhaust air from the box is conducted through a properly sized biofilter, to which an intermediate cleaning device may be added to keep the concentration of clean gas at 150 OU/m^3.

Completely enclosed composting plants (second case) actually emit odors by means of the purified exhaust air. Therefore, the volume of the exhaust air determines the source intensity of the plant. This results in the fact that a minimized exhaust air volume is decisive in achieving a favorable immission prognosis.

Subsequently, a rough comparison of the total volumes of exhaust air from composting halls being used and aerated by means of negative and positive pressure is carried out based on an example. A plant input of 20,000 Mg/year has been chosen for the example. An aeration rate at an average of $3\,\mathrm{m^3 air/m^3 \cdot h}$ was used for the compost.

The total area for the decomposition section of about 3800 m^2 with a height of 8 m amounts to a volume of the hall of 30,400 m^3. A net hall volume of 23,800 m^3 remains to be de-aerated if the volume of the compost of 6600 m^3 (10 weeks' decomposition) is subtracted. Based on a simple air ventilation in the hall (no permanent working place), 23,800 m^3/h must be discharged from the hall.

When there is aeration by negative pressure and the exhaust air from the windrow (19,800 m^3/h) is calculated in the ventilation number of the air, 4000 m^3/h of air remain, which have to be supplied for purification as hall exhaust air.

Table 11.24. Example for odor emissions of a composting plant with an input of approximately 6000 Mg/year

Location/units	Material quantity (m^3)	Composting on unaerated triangular windrows (OU/s) ($h = 1.60$ m)	Pre-installation of decomposition boxes (dwell time 7/14 days) (OU/s)
Bunker	46	390	390
Input			
Freshly prepared	23[a]	235	235
Covered	23[a]	40	–
Decomposition boxes			
Exhaust air	230/460	–	48/96
After biofilter ($5\,m^3/m^3 \cdot h$)		–	
Discharge (humid)	41/39		1120/640
Triangular windrows (static)	Approximately		
Maximum 14 days old	340[c]	680	–
Maximum 14 days old	160[c]	–	320/-
Over 14 days old	1300[c]	520	520
Triangular windrows (re-stacking)			
7 days old	41	1120	–
14 days old	39	640	640/-
21 days old	37	240	240
Decomposition degree >III[b]	Approximately 60[c]	72	72
Fine treatment[d]	23	28	28
Storage (12 weeks)			
Daily quantity, cut up	23	12	12
Storage windrow static	1380	235	235
Sum		4212	3860/2468

[a]Half of daily quantity.
[b]Re-stacking rhythm 14 days (2 windrows per day).
[c]Mean value.
[d]Like re-stacking at decomposition degree >III.

In case of pressure aeration and a single air exchange in the hall, 23,800 m^3/h must also be collected. As opposed to the windrows aerated by means of negative pressure, the use of forced aeration makes it possible for a partial circular supply of the hall exhaust air, which reduces the amount of the total exhaust air. If the circulating air is provided with 30% of the exhaust air from the hall, in this particular example 7140 m^3/h do not have to be supplied to the purification system for the exhaust air. The remaining air volume to be treated simultaneously with the emitted air volume is only 16,660 m^3/h.

Exhaust airflows (inlet air to the hall) from the bunker area, from the input preparation, and from the fine treatment area can be used for aerating the windrows. Even by minimizing air volumes (e.g., by enclosing individual processing units), this amount is still available, at least approximately 50%, which is sufficient for the aeration of the windrows during normal operations.

A comparison of the aeration systems regarding a highest possible reduction of the total exhaust air volumes of a composting plant shows that, in a plant with approximately 20,000 Mg/a throughput, up to 30% of the exhaust air volume from the decomposition area can be saved with forced aeration table windrows, in comparison to the windrows aerated by negative pressure. An optimized exhaust air purification system with odorant concentrations of $<250\ OU/m^3$ after the filter, provided in both cases, means that the odor load emitted from the exhaust airflow from the decomposition hall using forced aeration windrows is also reduced by 30%.

The special case of windrows that are aerated by both suction and by forced aeration, which use the exhaust air from the windrows as additional air from the portion that is aerated by means of negative pressure for aerating the portion that is aerated through forced aeration, can be compared in an air volume calculation with windrows that are entirely aerated by means of negative pressure and operated by circulating air. This means that for a plant with a 20,000 Mg/year input, using suction-aerated table windrows and operating with optimal air ventilation (multiple utilization, circulating air), the biofilter receives odorant loads of about 1700 OU/s with forced aeration and about 1200 OU/s from the exhaust air from the decomposition hall. The additional air volumes furnished to the exhaust air purification unit from other areas of the plant increase the emission mass flow correspondingly.

Rough estimations for a small plant (a throughput of about 6000 Mg/year) without enclosure and without special measures for the reduction of odors compared with a large-scale plant (a throughput of about 20,000 Mg/year) with windrows aerated by negative pressure show that the emissions from the decomposition area of the large plant are about 40% of the total odor load from the small plant. When forced aeration is used, this emitted load decreases to even 30% of the total load. The completely enclosed "large-scale composting plant," with optimized air ventilation of the exhaust air volume and an emitted odor load from the decomposition hall after the exhaust air was purified, with a throughput of about 20,000 Mg/year and a measured value of at least 50% of the total load, is still more favorable regarding the total emissions than the sample "small plant" with an annual throughput of 6000 Mg/year.

These calculations show that, before a composting plant is designed, the immission values to be stipulated for release into the environment must be calculated according to the admissible odor sources of this plant. Then, adequate planning can be carried out with the objective of an optimum process when it comes to odors.

Exhaust Air Purification

Biofilters using layers of compost, crushed bark, mixtures with swelling clay, broken root timber, fibrous peat, and heather are presently used in order to deodorize exhaust airflows loaded with odorous compounds. Heavily loaded exhaust airflows (e.g., from decomposition drums or from windrows aerated by negative pressure) must incorporate additional bio-scrubbers before the biofilter as the concentration of odorous compounds in the crude gas is too high to achieve satisfactory results of clean gas at a filter efficiency of >95%. The installation of a humidifier before the biofilter also reduces the concentrations of odorous compounds by washing them with the liquid.

A tendency to use multiple-stage exhaust air procedures is inevitable to meet future requirements of odor emissions, which are expected to be more stringent for biological waste treatment plants. This can lead to combinations of bio-scrubbers and several biofilters connected in series. In the future, the collection of exhaust airflows after their purification and their discharge via chimneys must be considered due to the positive impact of the increased source height on the immission values (see Section 11.3.1, Dispersion Mechanisms of Odors).

If all conditions mentioned in the previous paragraph and in Section 11.8, Odor Immission Cases in Composting Plants, are fulfilled, it can be assumed that an optimal air management can be found for partially or completely enclosed composting plants. The optimal air management is specific to the individual plant technology and reduces to a minimum the external effects of the plant operation arising from the emission of odorant concentrations.

The data in Table 11.25 show a summary of relevant odor data for an enclosed composting plant with an annual throughput of 12,500 Mg/year. This example is taken in the following three figures to demonstrate the effects of the air ventilation inside the plant on the source intensity of the biofilter. The example largely corresponds to a modular type IV plant (windrow composting aerated, see Section 11.5, Modular Types of Composting Systems and their Respective Odor Emissions).

In this case, the emitted odor load from the biofilter can be reduced by approximately 30%, as opposed to the original plan of multiple utilization of the airflows (Fig. 11.20). Of course, the following must be considered. If exhaust air from individual plant areas is ventilated into other operational sections of the plant, the portion of additional air used must only be 60–80% of the amount of air discharged from the same section. The rest of the air should be suctioned by means of fresh air ventilators. In this way, a steady light low pressure can be maintained, thus avoiding the discharge of odorants. An example of optimized air ventilation is given in Fig. 11.21.

During special operational conditions (e.g., maintenance work), it may become necessary to bypass or to switch off used additional airflows in order to improve the environment in the specific portion of the plant (Fig. 11.22).

11.7. Preparation of Dimensioning Sheets for Odor Calculation in Composting Plants

The dimensioning sheets described previously are designed to standardize and simplify the assessment and calculation of odor emissions and immissions. This objective is achieved when all composting methods actually available on the market are allocated to the 6 modular types. The basis for the dimensioning, i.e., the odor data, was taken from the data

Table 11.25. Values of odor emissions of a composting plant with a throughput of 12,500 Mg/year (example)

Pos. 1	Source	Area (m^2)	Volume (m^3)	Surface (m^2)	Air stream (m^3/h)	Odorant concentration (OU/m^3)	Odor radiation (OU/$m^2 \cdot$ s)	Odor load (OU/s)
1.1	Material box, shredder material	25	50	70	–	500–1500	0.41–1.24	29–87
1.2	Intake hall	525	3570	–	3570	100–300		100–300
	Exhaust air intake hall	525	3570	–	**3570**	150–400	–	**150–400**
2.1	Pit bunker biowaste	50	60	80	–	1000–8500	0.83–7.04	66–560
2.2	Pit bunker green waste	166	500	300	–	150–500	0.12–0.41	36–120
2.3	Pre-comminution	–		30	–	1200–3000	0.99–2.49	30–75
	Exhaust air bunker area	270	2720	–	**5440**	200–800	–	**300–1210**
3.1	Preparation hall	216	1750	–	3500	300–500	–	290–490
3.2	Encapsulated units	–	–	–	500	2160	–	300
	Exhaust air coarse preparation	216	1750	–	3500	610–810	–	590–790
5.1	Table windrow storage	340	1000	400	–	250	0.21	84
5.2	Pile/cut up	–	–	120	–	1200	0.99	120
5.3	Screening unit (passive)	–	–	150	–	1200	0.99	150
5.4	Bagging unit (passive)	–	–	50	–	300	0.25	13
5.5	Exhaust air screening and bagging	–	–	–	500	600	–	83

(*continued*)

Table 11.25. Values of odor emissions of a composting plant with a throughput of 12,500 Mg/year (example) — *Cont'd*

Pos. 1	Source	Area (m^2)	Volume (m^3)	Surface (m^2)	Air stream (m^3/h)	Odorant concentration (OU/m^3)	Odor radiation ($OU/m^2 \cdot s$)	Odor load (OU/s)
	Exhaust air fine preparation and storage	867	4760	–	**9520**	170	–	**450**
4.1	Additional air, decomposition hall[a]	–	–	–	18,460	260–480	–	1340–2450
4.2	Windrow negative aeration	1750	2800	1780	–	300–800	0.25–0.66	445–1170
4.3	Windrow forced aeration	1750	2800	1780	5040	500–3000	–	700–4200
4.4	Re-stacking negative aeration windrow	–	–	450	–	1500–4500	1.24–3.73	560–1680
4.5	Re-stacking forced aeration windrow	–	–	450	1275	1200–5000		425–1770
	Exhaust air decomposition hall	4320	33,100	–	**33,100**[b]	1170–2090	–	10,760–19,220
					66,200[c]	580–1040		10,670–19,120
7.1	Container for residues	–	–	20	–	500–2500	0.41–2.07	8–41
7.2	Discharge screening unit	–	–	80	–	250–1200	0.21–0.99	17–79
7.3	Traffic areas, outside	1000	–	–	–	50–200	0.04–0.17	40–170
7.4	Other diffuse sources	–	–	–	–	–	–	200
	Maximum total emission active	**–**	**–**	**–**	**33,100** **66,200**	250 250	– –	**2300** **4600**
	Maximum total emission passive	–	–	–	**–**	–	–	**490**

[a]Optimized air ventilation, exhaust air streams from the bunker are included intake hall, coarse preparation, and fine preparation.
[b]Normal operation with simple air change per hour in the decomposition hall.
[c]Maintenance work with twofold air change per hour in the decomposition hall.

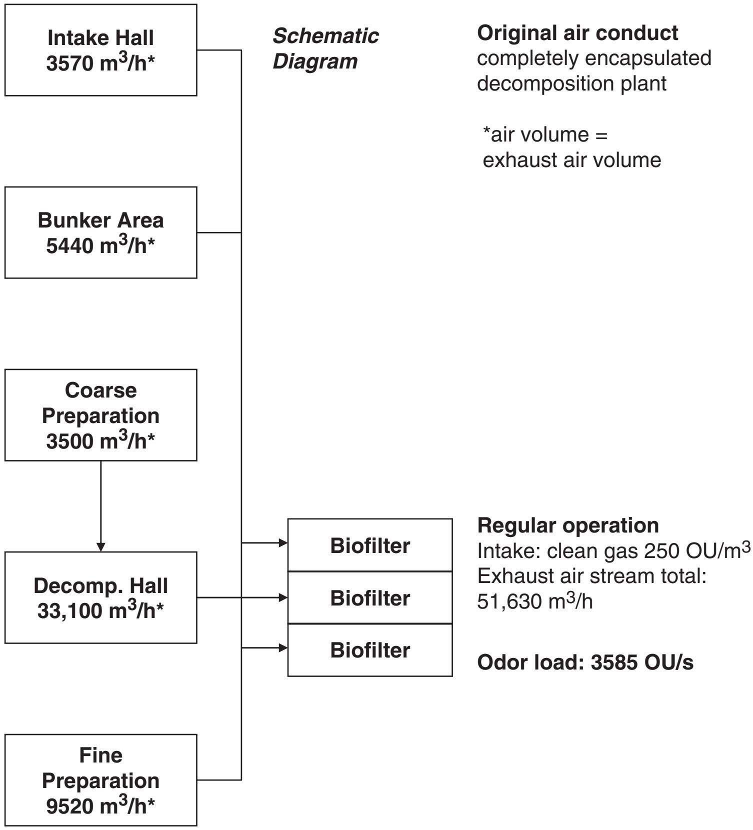

Fig. 11.20. Example of non-optimized air ventilation (data from Table 11.25).

in the literature review in Section 11.5, Modular Types of Composting Systems and their Respective Odor Emissions.

The precondition for a correct assessment of the emissions is a permanent characterization of the planned plant. A continuous actualization of the basis of the data is inevitable.

11.7.1. Structure of the Dimensioning Sheets

The dimensioning sheets are divided into two parallel levels. One describes the emissions and their influence on the specific process steps and the other level describes the generally valid process steps which can be found in every method. Fig. 11.23 illustrates the structure of the dimensioning sheets with the two parallel levels. Six individual modular types are listed as the main levels and the specific and general process steps with their

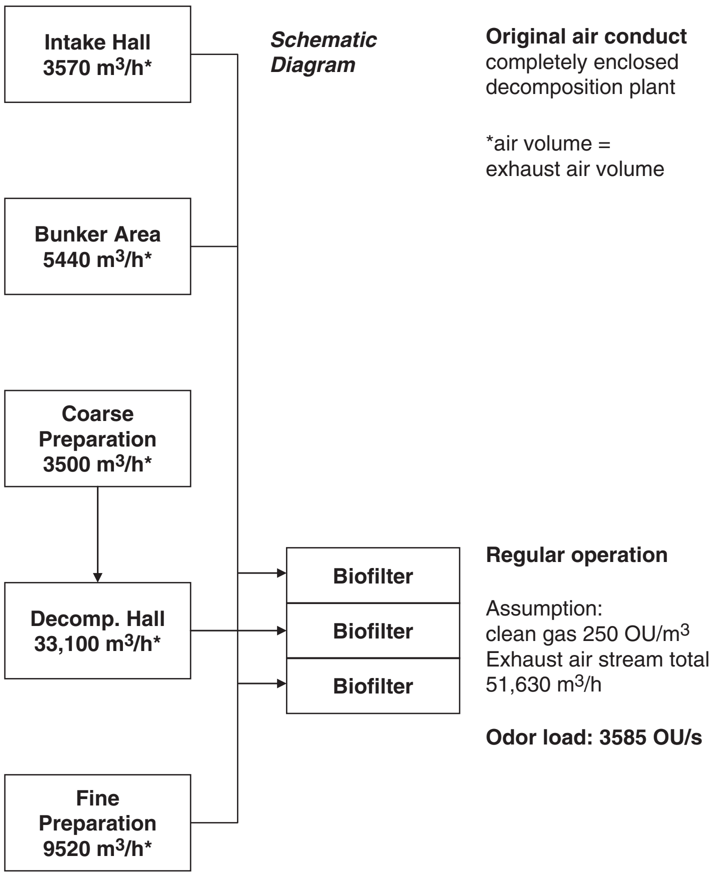

Fig. 11.21. Example of optimized air ventilation (data from Table 11.25).

respective influence as the two sublevels. The individual levels are described in detail in the following section and are documented with figures, from composting Type I as an example.

Main Levels I–VI

The main level is shown in Fig. 11.24 as an example of box/container composting. This level describes the process type by means of a flowchart. Within this flowchart, there are individual steps displayed in two different colors. The steps with a light-colored background describe the level of the generally valid process steps and the dark-colored background describes the level with the specific parts of the procedure.

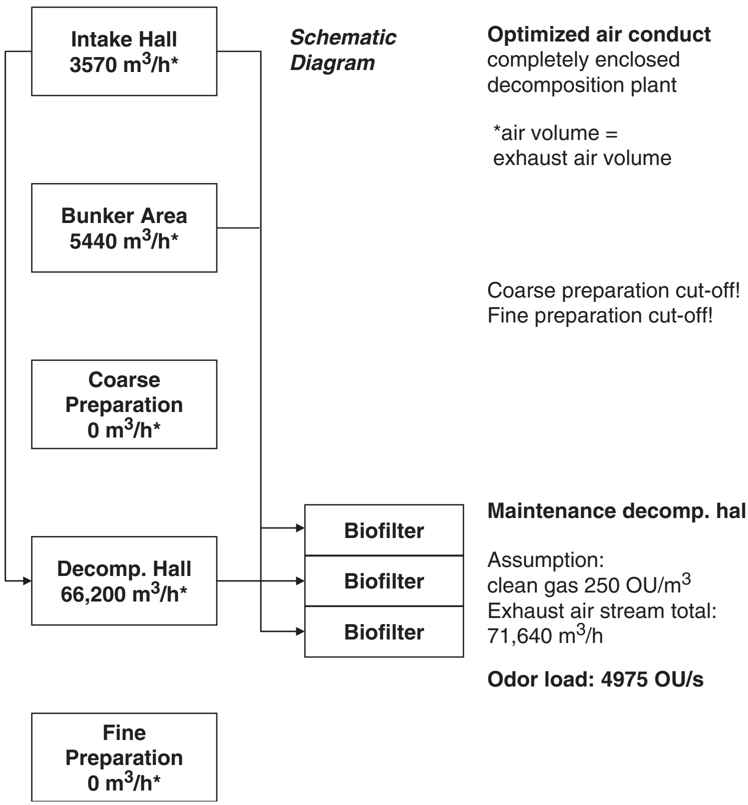

Fig. 11.22. Example of optimized air ventilation during maintenance in the decomposition hall (data from Table 11.25).

Sublevels I–VI (Specific Process Steps)

The process-specific partial modular components such as decomposition and subsequent decomposition and their emissions are listed in this sublevel. In this section, all of the emitting working steps within the process-specific steps and the possibilities for exhaust air together with the corresponding odorant concentrations are dealt with. Additionally, the corresponding influencing parameters are named to all possible emissions. These are necessary since often very large ranges of deviations take place within the concentration (see Section 11.4, Assessment and Comparison of Odor Data). These influencing parameters could be, for example, the moisture content or the decomposition time of the material. Sublevel I of the box and container composting is shown in Fig. 11.25 as an example.

Influencing Parameters of Sublevels I–VI

More closely described in this level are the previously named parameters that influence the individual emitting sources. This level is meant to assist in the assessment of odorant

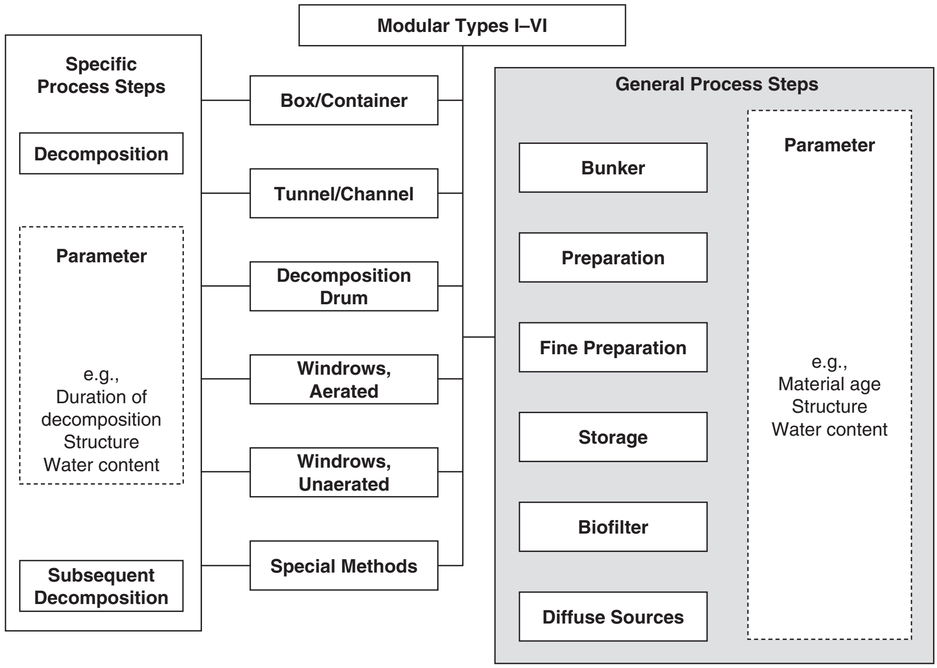

Fig. 11.23. Structure of the two parallel arranged levels of the dimensioning sheets.

concentrations that fall between larger deviations. As far as this is possible, the concentrations are more intensely allocated and made transparent. Fig. 11.26 shows examples of influencing parameters of sublevel I for box and container composting.

Levels A–F (Generally Valid Process Steps)

Parallel levels to sublevels I–VI are the general process steps such as the treatment or the delivery of biowaste, assigned letters A–F (see also Section 11.5, Modular Types of Composting Systems and their Respective Odor Emissions). They are equally designed and have a level that describes the influencing parameters, as described above. The design of the two levels is shown in Figs 11.27 and 11.28 as examples of the process step preparation (level B).

11.7.2. Handling of the Dimensioning Sheets

To simplify the use of the dimensioning sheets, the procedure is shown by means of an example.

If the planner of a composting plant made the decision to use a particular composting system, the first question is which modular type will be used. If he decided on a modular

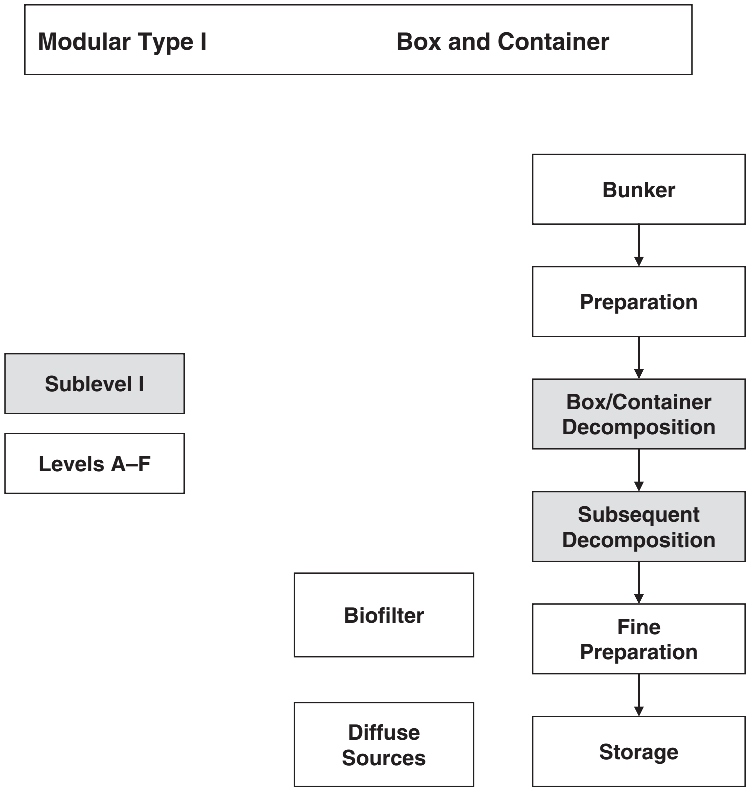

Fig. 11.24. Main level of modular type I.

type, in this case modular type I, he must choose the level (general or specific process steps), which has to be covered. In the example it is sublevel I, i.e., the process-specific sublevel. Within this sublevel, he can choose between two different possibilities (see Fig. 11.29), in this case decomposition and subsequent decomposition.

In the event that decomposition was selected which is subdivided into areas relevant to the emissions, such as material input and discharge, material surface, re-stacking procedures, etc., in this sequence, the material discharge was chosen as an example, which is quoted to have an odorant concentration of 120–30,000 OU/m^3. In order to simplify the selection of the level of the odorant concentrations for each emission relevant area, as far as possible, influencing parameters have been determined together with their respective odorant concentrations. These influencing parameters are, for example, the moisture content of the material, the time of decomposition, etc. (see also Fig. 11.26).

The moisture content of the material was chosen as an example of a parameter. In this case, the concentrations increase as the moisture content increases. With a moisture content of 50–60%, the odorant concentrations vary between 11,000 and 16,000 OU/m^3.

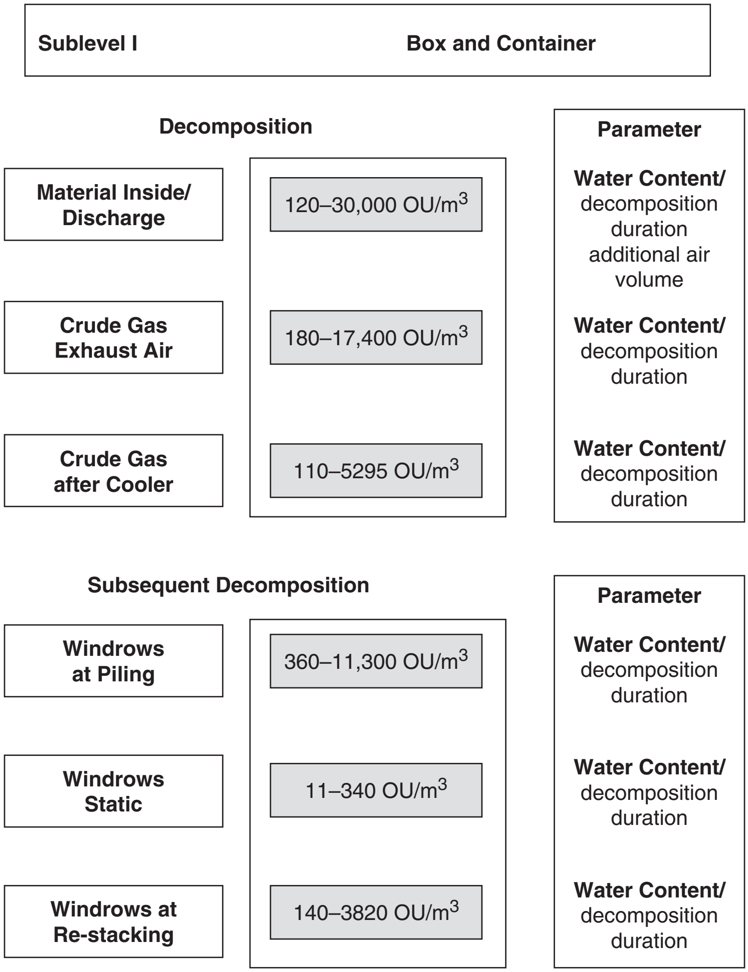

Fig. 11.25. Sublevel I of modular type I.

11.8. Odor Immission Cases in Composting Plants

11.8.1. Collection and Evaluation of Concrete Cases

The operational experiences collected from eight composting plants with a throughput between 7000 and 35,000 Mg/year and with substantial odor problems have been evaluated, together with the experiences of a couple of other works in the range of emissions from odorants. Most of the plant managers made their data available on the condition of anonymity for the individual plant site and its specific problems. Therefore, only general statements are made.

Sublevel I
Parameter

Box and Container
Decomposition

Water Content

The higher the water content, the higher the odorant concentrations:
Material Surface
WC 30% - 40%: 120–1220 OU/m^3
WC 40% - 50%: 2740 OU/m^3
WC 50% - 60%: 11,300– 5,900 OU/m^3
Crude Gas: after 7 d humid, minimum delivery air: 15,940–30,000 OU/m^3
1–7 d, dry: 10,100–176 OU/m^3

Decomposition Duration

Decomposition duration in the reactor:
at optimal WC decrease the concentrations:
10,000 OU/m^3 on the 1st day
180 on the 7th day with dry material
with humid material, up to 30,000 OU/m^3 on the 7th day

Delivery Air Volume

Odorant concentrations in the crude gas decrease at higher additional air volume:
humid material:
50 $m^3/m^3{\cdot}h$: 30,000 OU/m^3
20 $m^3/m^3{\cdot}h$: 200–10,000 OU/m^3 (7 days)

Basis of calculation related to 1 m^3 material
at a small plant with 6500 Mg/year:
delivery air 5 $m^3/m^3{\cdot}h$: 41 OU/($m^3{\cdot}s$);
delivery air 20 $m^3/m^3{\cdot}h$: 30 OU/($m^3{\cdot}s$);
discharge, humid (daily quantity approx. 41 m^3); 27 OU/($m^3{\cdot}s$);
delivery air 25 $m^3/m^3{\cdot}h$, 7d, WC < 40%: 1.4 OU/($m^3{\cdot}s$)

Fig. 11.26. Influencing parameters for sublevel I of the modular type I.

Apart from the assessment of the available data such as approval decisions, reports of emission assessment, expert opinion for the immission situation and for the decomposition management, etc., additional background discussions have been carried out with several plant managers and with experts from approval and other regional authorities in order to obtain a clear picture of the individual local situation.

In the past, the inevitable odor emissions arising from the operation of composting units have led to considerable annoyances in the neighborhood of some composting plants. As a plant site can operate in the long-term only if the neighbors are not extremely annoyed, avoidance of damage caused by odors is of considerable importance. It is extremely

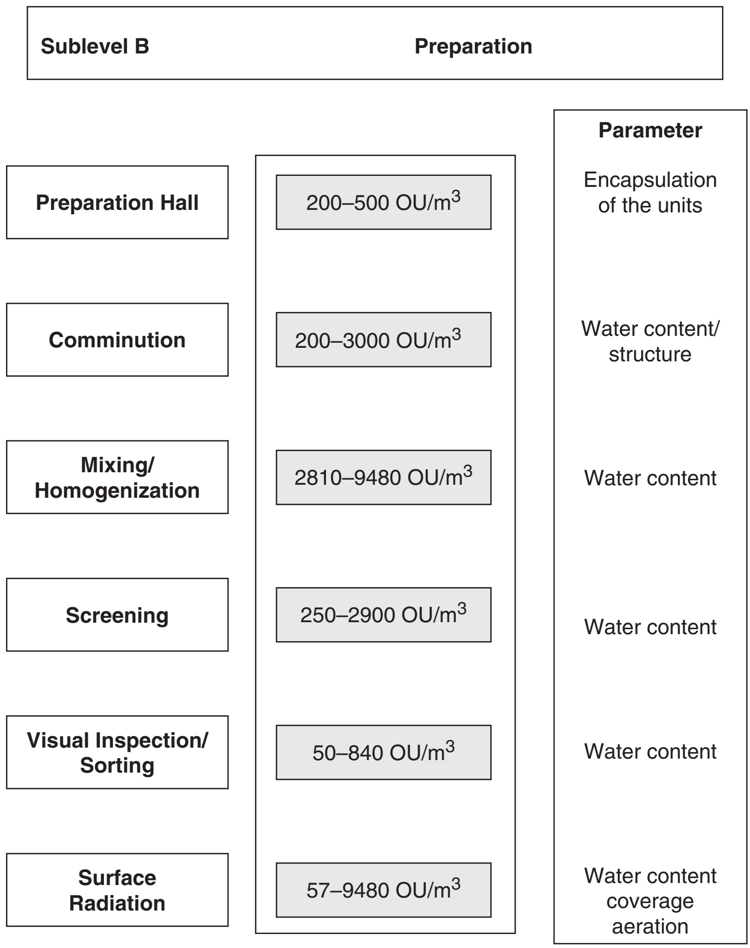

Fig. 11.27. Level B — preparation.

difficult to operate a composting plant entirely free of odors because of the mechanical and biological processes of the composting of waste material. An acceptable situation for the environment can be created only through proper planning, equipment selection and operation, and operational management.

In addition to site selection, the essential influences on the outer effects of odors of a composting plant are:

- plant throughput and the type of processed wastes,
- the selected decomposition process,
- the extent of enclosure of the odor-emitting units,

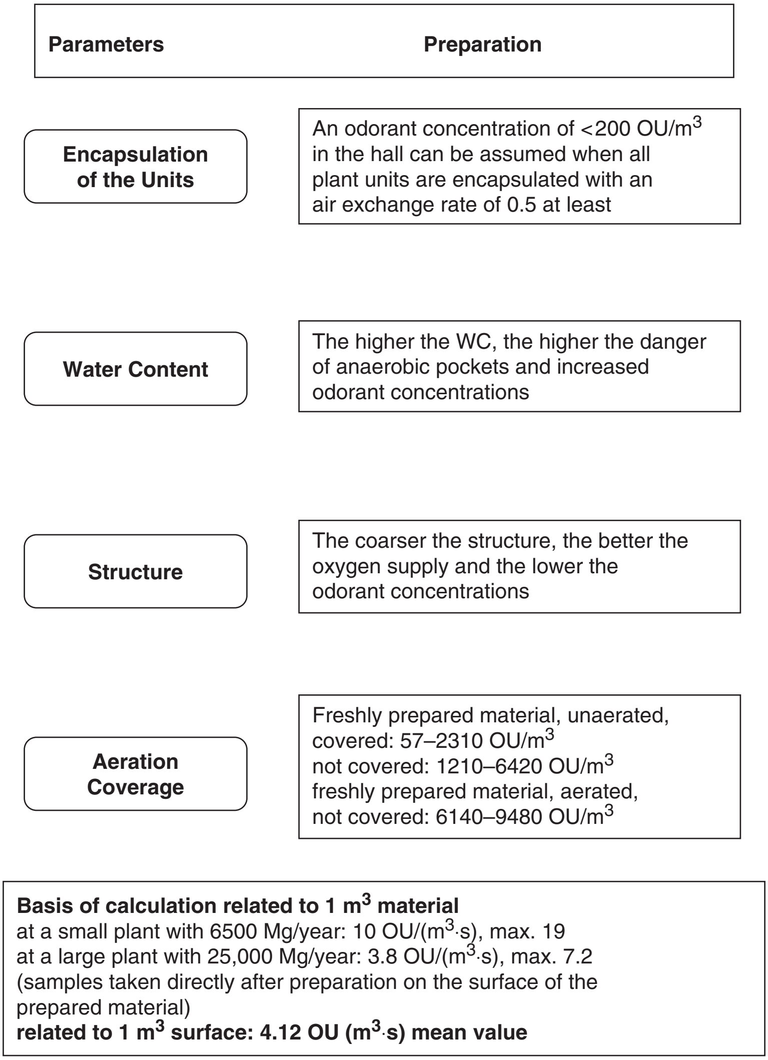

Fig. 11.28. Parameters for sublevel B.

- the achieved purification efficiency in exhaust airflows from enclosed plant units, and
- the operational management.

The analysis of the considered damages shows that the following problems arise on a regular basis:

- underestimation of the odorant concentration of the selected composting technology already in the planning stages and correspondingly insufficient measures regarding protection from emissions,

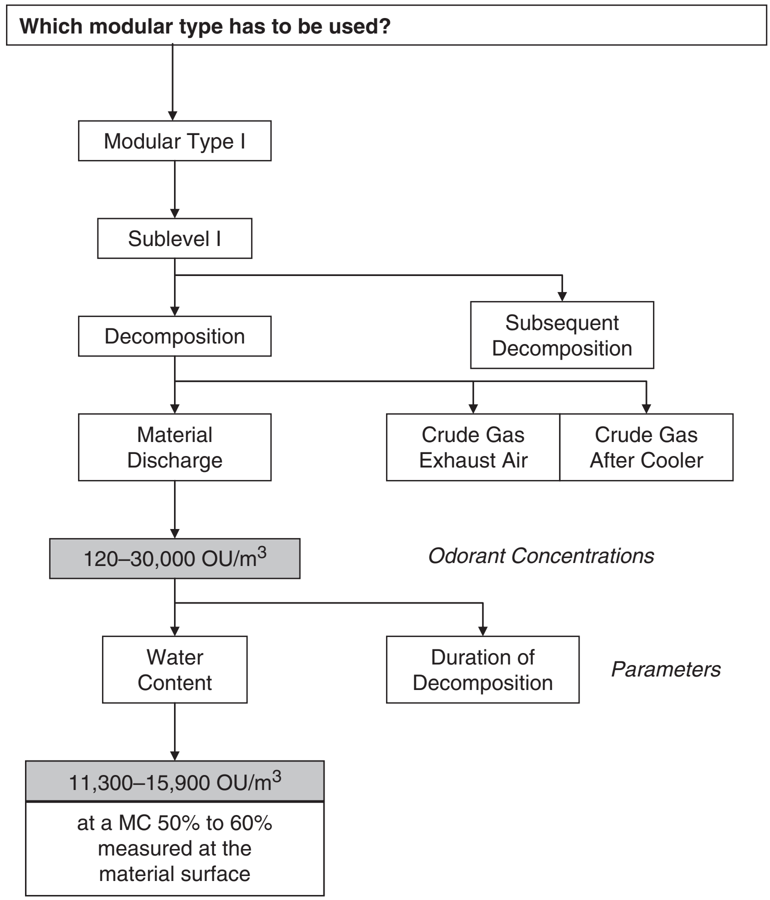

Fig. 11.29. Method for the use of the dimensioning sheets by means of a sample modular type.

- technical problems during the operation of composting plants resulting in unforeseen operational conditions with higher emissions,
- incorrect dimensioning of the decomposition unit with the result of a very low degree of decomposition in the mature product (e.g., decomposition degree II instead of IV), with heavy odor emissions in the compost refining and in the storage areas,
- careless operational management, which does not correspond to the demands of the emission protection (i.e., open gates, other diffuse sources),
- underestimation of the impacts of "small" odor sources such as open containers for residual waste or open transport of fresh compost,
- technically insufficient or incorrectly dimensioned purification units for exhaust air and poor air management (i.e., filter material, crude gas conditioning),

- insufficient control and maintenance of the purification units for exhaust air (i.e., filter maintenance),
- minimization of complaints from neighbors through the plant operator with entailing escalation of the quarrel over tolerable conditions in the surroundings of the plant, as well as abuse of the situation by neighbors who believe they can make a profit if they emphasize the problem of a principally tolerable immission,
- delaying solving the problem due to costs or loss of image, and
- encroachment of residential buildings or industry on the borders of the composting plant after the initial operation.

Several of the problems listed usually come together; consequently, some operators have already discussed the possibility of closing down the facility at the present location.

At this point, none of the known weaknesses of the dispersion calculation and of an immission prognosis for odorant concentrations according to the Technical Guidelines are well understood. Air should be discussed; however, the mistakes made at the combination of the input parameters (i.e., the strength of the source of individual process units rich in emissions) should be considered. Very often, ideal basic conditions are assumed as the bases for a calculation, although since the beginning of the 1990s sufficient odor measurements have been made available which document the total range of possible strong odor emissions from individual odor sources.

Prognosis for emissions and immission of odorant concentrations are usually made together with the planning for approval, i.e., actual data related to the aeration technology that would be used later and the air management are, in most cases, not available. The often uncomfortable expert's job for immission and emission is the demand from the plant's planning office and the owner of the plant to meet the allowable emission values in the neighborhood of the site, which probably would increase the costs for the project considerably and even exclude certain plant configurations such as the operation of open windrows or similar technologies.

The consequences of an emission/immission prognosis that has been conducted during the planning process or on the basis of not as yet clearly defined operational specifications could be either the determination of limit values for emissions by the approval authorities, which cannot be kept with the available technology during continuous operation, or the emission of essentially higher odor loads than obtained in the prognosis. In both cases, it is required to implement very costly retrofitting or modifications of the operational functions following from exceeding limit values or from odor annoyances from the neighborhood.

A conscientious investigation of the meteorological conditions at the planned plant location is necessary, e.g., consideration of the cold airflow or frequency of atmospheric inversion conditions. The costs associated with a detailed data collection program of the meso-climate at the location will be essentially inferior to the measures for emission protection in the existing plant.

It must be pointed out that an investigation of the status quo prior to the initial operation of new composting plants must be accompanied by the assessment of all existing sources of odor. This can be conducted through either field measurements carried out by panels in accordance with the GIR or by measurements, i.e., conscientious assessments of the source intensity of these emissions and inclusion in the immission prognosis. The data collection of the pre-load of the site environment according to GIR protects the manager of the composting plant from unjustified complaints later in the process.

Plant Operation in General

Of course, optimal plant operation can partially, but not entirely, compensate for planning mistakes. However, the analysis of the investigated damages shows that certain failures, which are independent of the plant's equipment, will occur over and over again.

Some of the failures include:

- delivery of already odor-intensive wastes, e.g., because of longer collection intervals of biowaste in the summertime (alternating, usually 2-week collection interval),
- longer intermediate storage of wastes in the bunker or delivery area prior to processing, e.g., because of a plant downtime,
- processing of excessively wet materials (e.g., from catering, restaurants, or markets) during a simultaneous lack of bulking material,
- plant units that are normally closed are left open, especially in the treatment and decomposition area; this behavior causes heavily increased diffuse odor emissions,
- regular cleaning of all traffic areas to avoid emissions of diffuse odor is not carried out,
- transport of odor-intensive material during unfavorable wind directions (e.g., toward the neighbor) or during corresponding meteorological conditions (e.g., inversion) with open windrows, but also in the storage area,
- overloading of the plant by a throughput that is too high. In this case, doubling effects regarding the emission intensity are the result, as e.g., windrows are piled too high (open-air plants), decreasing decomposition degree of the mature product (higher emissions during subsequent decomposition steps, at refining and in the storage area). Overload of the composting storage (windrows too high or windrows in the storage area that are not treated). A renewed self-heating of the compost and thus increased odor emissions. Overload of the purification unit of the exhaust air on account of the increased odor loads from all plant units, which are used more intensively. A generally incorrect working method on account of the lack of time (insufficient cleaning, monitoring, and maintenance work are carried out too late and/or incorrectly),
- neglecting the regular monitoring and maintenance of the purification unit for the exhaust air and other measures to reduce emissions (e.g., covering of open windrows with prunings or a canvas specially made for this purpose),
- insufficient reactions to accidents like breakdown of ventilators or individual units (for example: input in decomposition hall is stagnant, which leads to overloading of the bunker area with untreated wastes or prolonged storage time),
- disregard of the standards for air management (e.g., multiple utilization of airflows), thus higher exhaust air volumes in the clean gas flow with a corresponding increase of the emitting odor loads (only with plants that are partly or totally enclosed), and
- material transfer and discharge points between individual units with faulty construction and not properly adjusted, therefore continuous soiling of the ground (coarse and fine treatment), which leads to diffuse odor sources.

Purification of Exhaust Air

The operation of an exhaust air purification plant, which in partly enclosed composting plants nearly always is composed of a biofilter, possibly in combination with a bio-scrubber, presupposes proper training and experience of the operating staff. Like all biological systems, biological exhaust air purification units also need continuous monitoring and maintenance if they are going to be operated with optimal effectiveness.

If odor annoyances arise in the neighborhood of a composting plant that are caused by malfunctioning of the exhaust air purification, the following may be possible reasons:

- The biofilter material is exhausted, the purification efficiency decreases continuously.
- The used filter material does not meet the requirements and tends to compact, does not decompose properly or has high maintenance expenditures (keywords: high pressure loss, ruptures, frequent loosening).
- The water management in the biofilter is not balanced, dry zones are developing, which lead to ruptures in the filter.
- The raw gas does not flow into the biofilter in a constant manner (e.g., clogging in the slatted floor), preferential channels are developed leading to an increased area load. The consequences are increased emission values or even filter ruptures.
- The filter control and maintenance is neglected; therefore, arising problems such as erratic flow behavior, dry zones, etc. will not be noticed in time.
- The design of the exhaust gas purification is defective. This causes problems, especially with the suction portion of the exhaust gas filter because of high exhaust gas concentrations and temperatures, which can only be repaired by a previously connected exhaust gas conditioning unit such as a bio-scrubber.
- The air management of the composting plant is defective, the previously connected bio-scrubber or the exhaust air conditioning do not work properly, so that the biofilter is loaded with concentrations of raw gas and/or temperatures that are too high. This, as a rule, leads to an increase of the purification efficiency (efficiency degree in %) with a filter that is in good order; however, it causes a distinct increase of the concentration of clean gas and thus an increase of the delivered odor load.
- The construction of the filter is defective (uniform crude gas distribution, simple cleaning of the delivery air management, easy access to the underground filter units).

Longer lasting, unplanned odor emissions at smaller plants that reduce their emissions from open windrows by covering (layers of prunings or canvas) arise only after the restacking process, when the fresh windrows are not covered immediately or the cover or canvas is not placed properly.

Public Relations and Management of Complaints

The staff of composting plants for biowastes are usually not properly trained for dealing with people who feel threatened in their rights or their physical integrity. This is especially necessary if a distinct emission of odors arise in the neighborhood of composting plants. In this particular case, the persons making the complaints should be approached with a little psychological cleverness and sympathetic understanding for their concerns.

These opportunities should be used immediately to recognize and, if possible, to remove weak points in the plant.

In every case where complaints due to odor annoyances came and were addressed only with tactics and appeasement, the conflict with the neighbors steadily increased. Negative newspaper articles, political discrepancies, and the establishment of citizens' action committees finally lead to high costs for staff and other expenses. The main reason for the quarrel, the odor annoyances, had to be removed anyway.

Of course, there are unacceptable complaints according to the regulations for the protection from immission where special interests or even monetary reasons play a role. In these cases, a possible settling of the conflict is the change of the residence of the complainant, which certainly is a costly undertaking, or an agreement on the basis of financial compensation. In both cases, the authorities concerned with the approval for the composting plant in question should be included in the decision-making process.

11.8.2. Proposals for Restoration and their Assessment

The problems described in Section 11.7.1, Structure of the Dimensioning Sheets, and the sources for avoidable odor emissions shown in Table 11.26 shall be the basis for restoration and general precautionary measures discussed in the following paragraphs. Fundamentally, it can be assumed that odor-emitting loads can be reduced with an advancing enclosure of the plant units (Table 11.26). This, however, shall not mean that open working composting equipment has to be refused or cannot be operated, as long as regulations are not relevant [see Technical Guideline of Urban Waste (TASI), GIR]. In fact it must be considered that due to costs, a degree of enclosure will be selected that is adapted to the special plant location.

Prognosis of the Odor Emissions

This is deduced from the procedure in the planning process. Determination of the decomposition-specific initial data article "prognosis of odor emission," the prognosis for the emission/immission of the odorants created for the performance planning has to be updated for the approval planning even until the initial operation stage of the intended plant. Only this can guarantee that all of the modifications or improved definitions of the emission situation are included in the prognosis of the odor immission in the plant environment, enabling a permanent feedback between plant planning and expected effect on the surrounding environment of the finished plant. Unpleasant surprises after initial operation of the composting plant, which could have been predicted, can be avoided by these measures.

Internal Concept

Due to the plant planner's need to keep the facility from emitting foul odors, the operator of the composting plant must be given corresponding instructions for required activities.

Table 11.26. Possible sources for avoidable odor emissions

Plant unit	Problems	Consequences	Possible remedies
Traffic areas	Impurities	Diffuse odor emissions	Strict observation of the cleaning program (at least once per workday)
Bunker	Odor-intensive delivery and/or wet input material	Increased odor emission (also in subsequent plant units)	Shortening of the collection interval (biowastes), preferred and rapid treatment (e.g., wastes from markets and restaurants)
	Longer interim storage of wastes (e.g., plant downtime)	Increased odor emission (also in subsequent plant units)	Joint agreements with other works in case of breakdown; in any case, collection on workdays
	Press water from collection vehicles	Increased odor emission in the bunker area and in traffic areas	Separate collection equipment for vehicles with press water tank, regular cleaning interval
	Open gates	Diffuse odor emissions	Automatic gates (e.g., remote controlling from the wheel loader), separation of the reception area and the bunker (sluices, mainly practicable with deep bunkers)
Coarse preparation	Wet input material	Clogging, press water, etc., increased odor emissions	Sufficient quantity of structure material
	Defective points for material supply	Material outlet from the material flow, impurities on the ground and on the units, therefore increased odor emissions	Retrofitting of the faulty plant units
	Odor-intensive residues	Increased odor emissions from the residual waste containers	Covering in the open area or general placement in the enclosed area under negative pressure
Decomposition	Material movement in unfavorable weather conditions/wind direction (open decomposition)	Increased odor emission in the direction of the next neighbors	Readjustment to the operating procedure

(*continued*)

Table 11.26. Possible sources for avoidable odor emissions — *Cont'd*

Plant unit	Problems	Consequences	Possible remedies
	Unsatisfactory decomposition progress (e.g., decomposition degree IV is not achieved)	Increased odor emissions at material discharge, in fine preparation, and in the storage	Optimization of the decomposition operation, probably decrease of the throughput or enlargement of the decomposition capacity
	Careless handling of the emission-reducing measures (e.g., coverage of open windrows after re-stacking)	Heavily increased odor emissions	Optimization of the operating process
Refining	Defective points for material transfer	Material outlet from the material flow, impurities on the ground and on the units, therefore increased odor emissions	Retrofitting of the faulty plant units
	Odor-intensive residual material (fresh compost)	Increased odor emissions from the residual waste containers	Covering in the open area or general placement in the enclosed area under negative pressure
	Not decomposed compost material	Increased odor emissions	Optimization of the decomposition operation, possibly a decrease of the throughput or enlargement of the decomposition capacity
Storage	Loading in open air	Increased odor emissions (fresh compost)	Enclosure of the plant unit or utilization of discharge hoses
	Not managed stock windrows	Renewed self-heating of the compost, increased odor emission when material is agitated	Conversion of the operation procedure (e.g., regular re-stacking, limitation of the windrow height, aeration of the stock windrows, etc.)
	Insufficient capacity	Increased odor emissions	Dislocation of surplus quantities, enlargement of the stock

All	Throughput that is too high	Decreasing decomposition degree, overload of all plant units, increased odor emissions	Strict limitation of the processed daily quantity, probably joint agreements with other works in case of breakdown
	Lacking cleanliness	Arising of diffuse odor sources	Strict adherence to the cleaning program (at least every workday)
	Lack of time and personnel	Inexact working method, lacking control and maintenance, thus increased odor emissions	Throughput limitation, more personnel
	Poor air management	Exhaust air volumes too large, thus increasing of emitting odor loads	Strict adherence to the standards, probably retrofitting/optimization of the aeration unit
	Lacking emergency management	Breakdowns of plant units lasting longer than necessary	Definite instructions for operation of breakdowns and a corresponding instruction of the personnel
	Open doors and gates in in-vessel plants	Generation of diffuse odor sources	Strict adherence to the corresponding demands, probably retrofitting of the gates for automatic operation by means of remote control, centralized monitoring of all gates and doors (closing detector)

These instructions should include:

- all necessary information for the minimization of odorous emissions during operation of the plant, such as, for example, the handling of the air management, the effects of the decomposition management, origination of diffuse odor sources, etc.,
- detailed information for monitoring and maintaining the units for the purification of the exhaust air, and
- a detailed description of emergency procedures, which also includes procedures for required maintenance.

An internal procedure for the avoidance of odorous emissions that are exceeding allowable limits should proceed from the following aspects:

- By corresponding experience and training, operational staff is capable of properly operating all of the units in the plant. Require presence of at least one very knowledgeable person to make key decisions during operational periods and the establishment of an emergency service outside of normal operating times. In case of an emergency, a responsible staff member who is capable of repairing failures should arrive at the plant within a short period of time.
- Maintenance of the plant units that are responsible for emissions (additional air units/exhaust air units, biofilter, etc.) should be conducted at regular intervals by means of a maintenance plan that considers the individual operation, respective downtimes of the units, and the requirements provided by the manufacturers. A storage room for keeping spare parts is self-evident.
- The following meteorological data should be continuously recorded for documentation of the climatic conditions at the plant site:
    - air temperature;
    - wind direction and intensity;
    - precipitation; and
    - relative humidity of the ambient air.
- Internal control of the wastes to be treated with the individual plant units takes place.

The prevention of avoidable odor emissions presupposes that when an enclosed composting facility is operated, it must be maintained properly:

- regular cleaning of the roads (daily on working days), of the outer areas (traffic areas, delivery of special wastes such as green wastes or wastes with a high moisture content, direct shipping of compost, etc.), of the shipping station of compost and the intake area should be carried out to avoid diffuse sources,
- gates to the hall will be opened only if it is necessary and closed immediately after use (e.g., installation of electrical sensors which allow the detection of open gates from the control room),
- automatic opening and closing of the hall gates (e.g., remote control from the wheel loader),

- no interim storage of wastes or compost in the outer areas,
- odor-loaded exhaust air discharged into plant units (multiple usage of airflows) will be removed in a proper way and these airflows will be transported to other enclosed and de-aerated plant units or directly to a biofilter,
- a control program exists for the aeration and de-aeration equipment with which the operational conditions of the total plant and individual plant units are monitored (e.g., day and night operation, maintenance of plant units which are operated automatically, emergency, new equipment of filter parts, minimum number of air changes, etc.), ensuring the maintenance of the standard conditions for the minimization of odorous emissions,
- a steady low, negative pressure is kept in the plant units to avoid generation of diffuse odors, and
- the requirements for filter maintenance and filter operation must be given priority (see the section "Exhaust Air Purification").

Exhaust Air Purification

The data in Table 11.27 summarize the malfunctions that often arise in plants with exhaust air purification (biofilter), their effects on the emission situation, and possible ways for solving problems. When operating a biofilter the following must be observed:

- when using the filter material provided, the maximum allowed load to the biofilter must not be surpassed during regular operation,
- an incremental change of the filter material at the remaining filter segments does not cause too strong a reduction of the purification efficiency (redundancy),
- the approved exhaust air value is guaranteed at the provided maximum load,
- the filter material be kept at a moisture content of $>40\%$ by suitable measures (additional air humidity, possible moisture addition),
- the requirements of VDI guidelines 3477 are to be observed regarding the dimensioning and the operation of the filter,
- the efficiency of the exhaust air blowers is dimensioned in such a way that the filter performance is not influenced by a compaction of the filter material and an increasing back pressure,
- the relative humidity of the additional filter air is kept, as much as possible, within the range of the water steam saturation (possibly assembly of a humidifier equipment),
- the temperature of the air delivered into the biofilter is within the range of $+10$ and $+40°C$,
- the structure of the filter is constructed in such a way that no ruptures arise, particularly in the border area,
- the air delivered into the biofilter is de-dusted as far as possible to avoid clogging of the air distribution equipment and of the lower layers of the filter,
- the pH in the biofilter material is kept at a neutral range, and
- a change of the filter media is carried out before the depletion of the purification efficiency is reached.

Table 11.27. Effects and maintenance of malfunctions of the exhaust air purification

Problems	Consequences	Possible remedies
High odor concentrations in the crude gas flow (e.g., from suction-aerated windrows)	High room load of the filter, despite high purification efficiency increased clean gas concentration	Crude gas refining respectively pre-connecting of a scrubber
Strongly changing odorant concentrations and/or high temperatures in the crude gas	Permanent change in the offer of nutrients and the environment for the microorganisms active in the filter	Mixture of different exhaust air flows, probably refining of fractional flows
Rapid and/or non-uniform degradation of the filter material	Increase of the pressure resistance in the filter, non-uniform purification efficiency, probably filter ruptures	Regular preparation and change of the filter material, use of filter material with a long detention time
Drying out of the filter material	Decrease of the purification efficiency till filter ruptures	Crude gas humidifying, irrigation equipment for the filter surface
Non-uniform flow against the filter	Decrease of the purification efficiency till filter ruptures	Regular control and if necessary cleaning of the delivery air ventilation
Non-uniform flow-off behavior	Decrease of the purification efficiency till filter ruptures	Regular control, preparation of the filter material, removal of drying out zones
Lack of nutrients in the filter material	Decrease of the purification efficiency till filter ruptures	Regular control, maybe refurbishment of the filter material
Worn out filter material	Decrease of the purification efficiency till filter ruptures	Regular control, refurbishment or replacement of the filter material

Furthermore, the following filter maintenance and control measures are recommended:

- visual monitoring of the filter surface (determination of ruptures and compaction in the filter material) if possible on a daily basis, the best time to perform the monitoring is in the early morning (due to the formation of water vapor),
- measurement of the temperature of the additional air and the airflow at least every working day,
- permanent monitoring of the humidity of the air is recommended, to cope with a possible drying out of the filter as quickly as possible,
- regular measurement of the filter back pressure (air supply to the filter) in order to identify compaction in the filter material,

- numerous determinations of the moisture content of the filter material during dry periods, other times only visually or at longer regular intervals,
- loosening of the filter surface at uneven off-flow behavior or fouling,
- regular sample collection from the filter material and determination of the pH and the concentration of volatile solids,
- regular monitoring of the operation of the irrigation equipment for the material irrigation and the additional air humidifier (if available),
- examination of the nutrient content (C, N, P) of the filter material at regular intervals, and
- cleaning the blower, the ducting for the delivery air, and the air distribution in the filter fields at regular intervals and the equipment associated with the delivery air humidifier (if available).

A bio-scrubber that is installed before a filter must be subjected to regular service and monitoring for proper functioning. Shredded root timber and screen residues (40–120 mm particle size) from green waste composting on surface biofilters were most successful with high exhaust air volumes (several ten thousand cubic meters per hour). The coverage for this filter type is spruce bark or similar with a grain size of 80 mm. Life expectancies of approximately 3 years (material from green waste composting) and 5 years (material from shredded root timber) can be achieved.

Currently, exhaust air humidifiers are used primarily for refining raw gas that is introduced into the biofilter; however, the humidifiers show a limited efficiency for the control of varying exhaust gas temperatures. In the event that the exhaust gas temperatures have a wide variation, the most effective remedy is to install a heat exchanger.

11.9. Summary and Outlook

Emissions from biological plants are currently playing an important role in the planning of a composting facility. The procedure for the official approval for the project determines the success of a plant today with the emissions to be expected and the willingness of the waste producers for a separate collection of the biowaste. An important component for the review and assessment of the emissions to be expected within the planning work for a plant was to create uniform standards. An initial basis was prepared with the current dimensioning sheets.

Depending on the difficulty for data collection, the dimensioning sheets are not complete in all points. The data were collected from both literature search in the framework of the DBU, sub-project 1 “connections between decomposition management and odor emissions at the composting of urban wastes” and literature research of publications that are accessible to the public, but also from unpublished measurement reports (Bidlingmaier and Müsken, 1994).

A difficult task was to include unpublished measurement reports, as odor data and hygiene data are looked upon as being very sensitive. Some of the composting procedures have too little detailed measurements for recording in the dimensioning sheets, e.g., the tunnel and windrow composting and composting in reactors and with bricks. Various data from the box and container composting could be used for some time because of the apparent similarity of individual procedures. The data gaps and the borrowing of measurement data should be validated with new measurements. Only by these means, the latest status of the measurement methods of odors can be represented.

After the assessment of all available measurement data, a system appeared that includes the following main points:

- classification of all procedures available on the market into 6 modular types to simplify the system,
- classification of the individual modular types into two types of process steps (generally valid and specific),
- allocation of the researched odor data into individual process steps, and
- influence of the parameters on the volume of the odorant concentrations within the individual process steps.

The simplification of the system was absolutely necessary as, for the time being, too many different manufacturers are on the market. The dividing of the modular-type system into two parts becomes meaningful if one considers the many process steps within the composting methods that are running parallel in nearly all types of procedures — here defined as generally valid process steps. This also concerns the classification in specific process steps included, above all, in the different decomposition systems.

The odor data are available in a relatively wide range of variation, the cause of which is on the one hand the different methods for measurement in the laboratories and on the other hand, the different preconditions during which the individual measurements were taken and which often were not known. In order to make the selection of the odor data easier for the person who uses the dimensioning sheets, known parameters have been included in the dimensioning sheets in order to minimize the variation limits. The know-how of the odorant concentrations at definite plant units is important for open or partly open plants, as here the odor emissions can be opposed with corresponding measures.

The air management in completely enclosed plants can be improved by the know-how of the odorant concentrations within the individual process steps. An exhaust air purification provided according to the state-of-the-art, influences only the emitted air volume, the source intensity of the plant, and thus the immission prognosis.

On the basis of the researched odor data, a computer program should be developed for improved and expedited dealing with the data assembled in the dimensioning sheets. An advantage of such a program would be to calculate the odor loads under certain conditions with the previously selected odorant concentrations and the individual air volumes of the planned plant. The air management of the plant could be optimized in such a way. Additionally a worst case scenario could be carried out.

11.10. References

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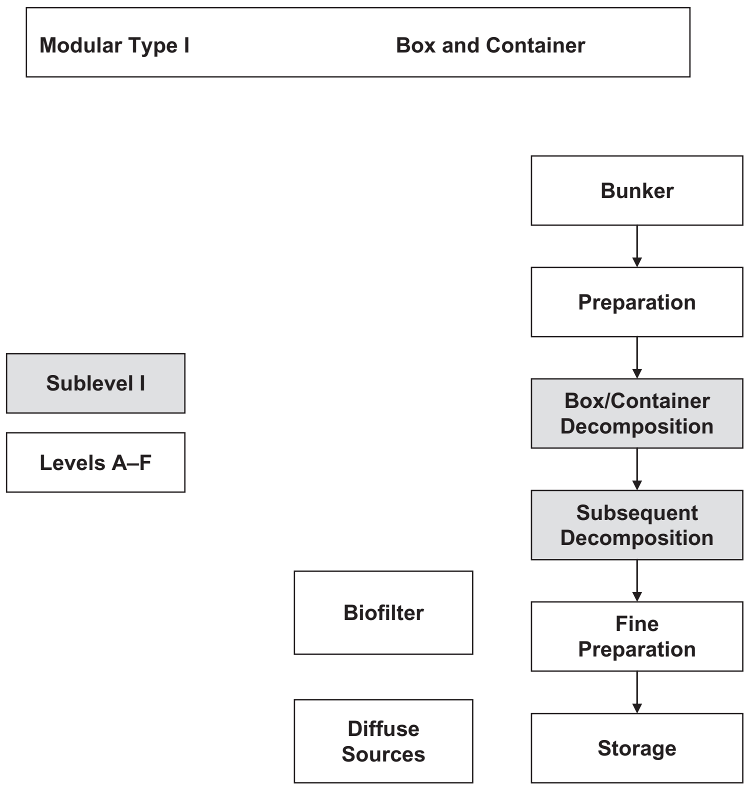
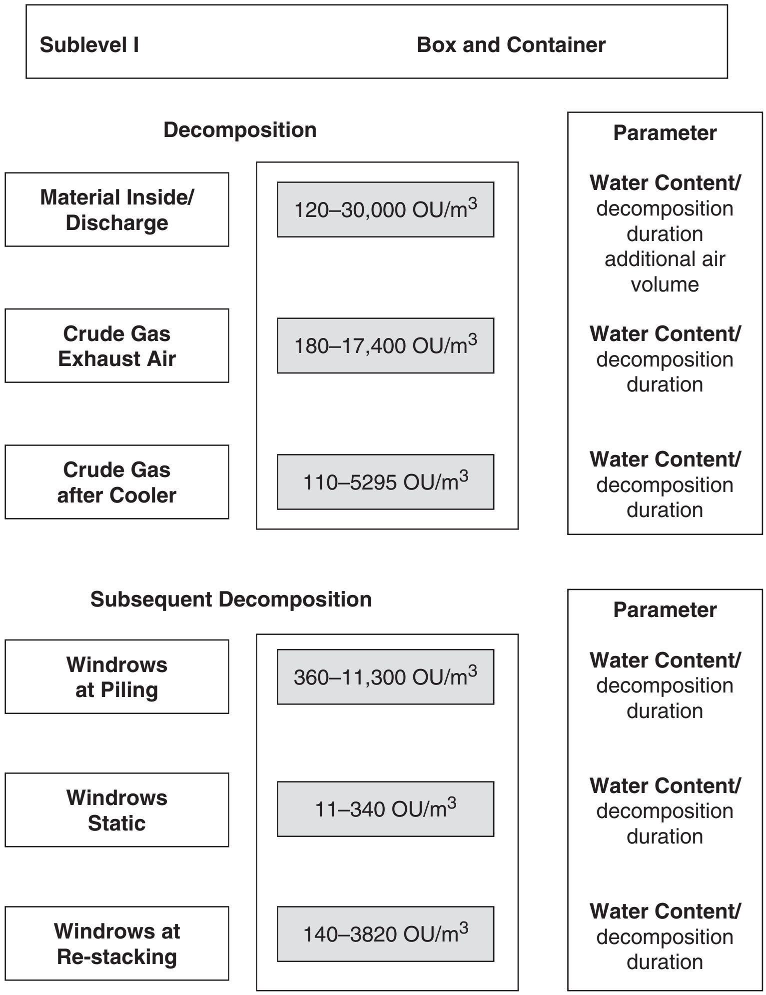
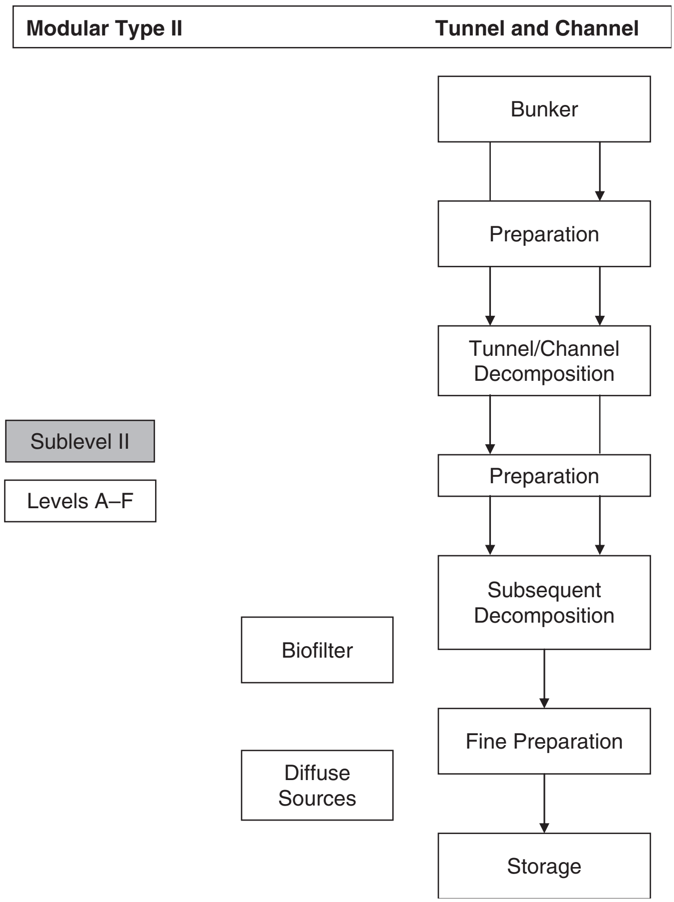
Annex A. Modular Types: Dimensioning Sheets



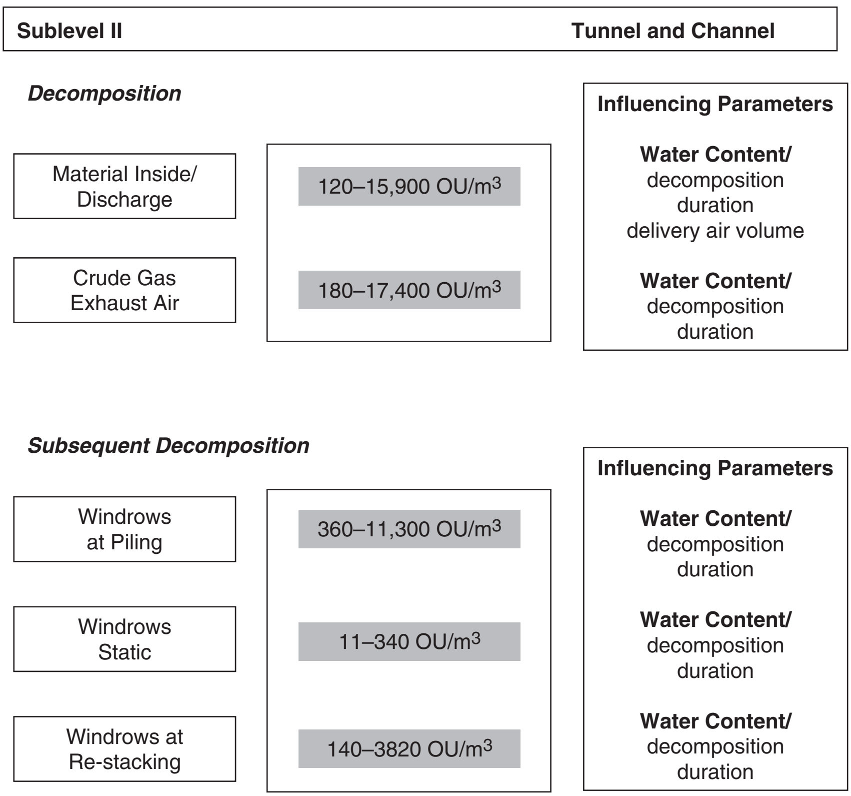
Modular type I — box and container



Sublevel I of modular type I — box and container



Modular type II — tunnel and channel



Sublevel II — tunnel and channel

Sublevel II Parameter	**Tunnel and Channel Decomposition**
Water Content	The higher the water content, the higher the odorant concentrations: **Material surface:** WC 30 to 40%: 120 to 1220 OU/m^3 WC 40 to 50%: 2740 OU/m^3 WC 50 to 60%: 11,300–15,900 OU/m^3 **Crude gas:** after 7 days humid, minimum delivery air: 15,940 to 30,000 OU/m^3, 1 to 7 days, dry: 176–10,000 OU/m^3
Decomposition Duration	Decomposition duration in the reactor; at optimal WC decrease the concentrations; 10,100 OU/m^3 on the 1st day, 180 on the 7th day with dry material; with humid material up to 30,000 OU/m^3 on the 7th day
Additional Air Volume	Odorant concentrations in the crude gas decrease at higher delivery air volume, humid material: 50 $m^3/m^3 \cdot h$: 30,000 OU/m^3; 20 $m^3/m^3 \cdot h$: 200 to 10,000 OU/m^3(1–7 days)

Basis of calculation related on 1m^3 material:
at a small plant with 6500 Mg/year
delivery air 5 $m^3/m^3 \cdot h$: 41 OU/($m^3 \cdot s$);
delivery air 20 $m^3/m^3 \cdot h$: 30 OU/($m^3 \cdot s$);
discharge, humid (daily quantity approximately 41 m^3): 27 OU/m^3s);
delivery air 25 $m^3/m^3 \cdot h$, 7 d, WC < 40%: 1.4 OU/($m^3 \cdot s$)

Influencing parameters for sublevel II — tunnel and channel

Sublevel II Parameter | **Tunnel and Channel Subsequent Decomposition**

Water Content

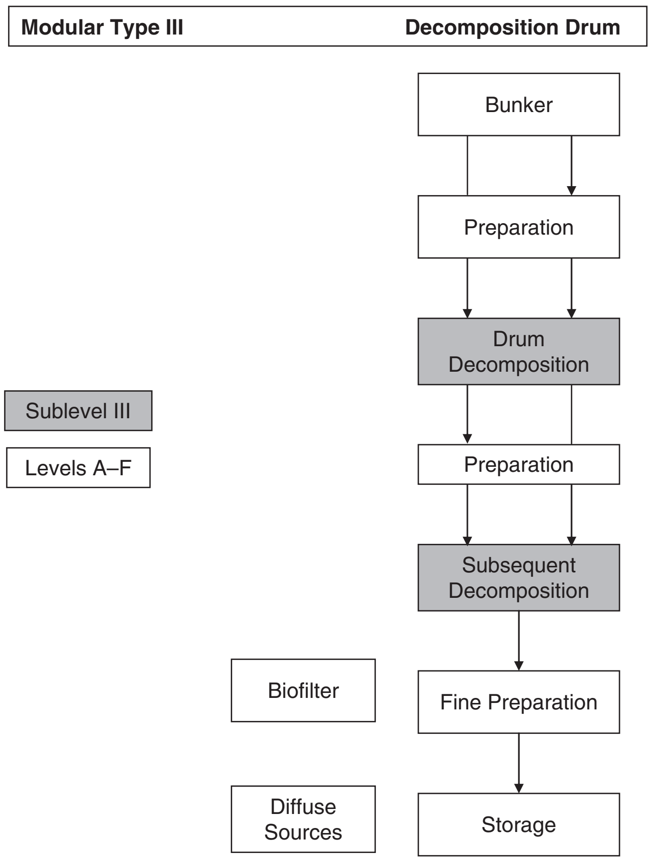
The higher the water content, the higher the odorant concentrations:
Dry material (WC 30 to 40%):
static: 11 to 340 OU/m^3
cut up: 140 to 340 OU/m^3
after re-stacking: 350 to 3820 OU/m^3
at piling: 360 OU/m^3
Humid material (WC 50 to 60%):
at piling: up to 11,300 OU/m^3

Decomposition Duration

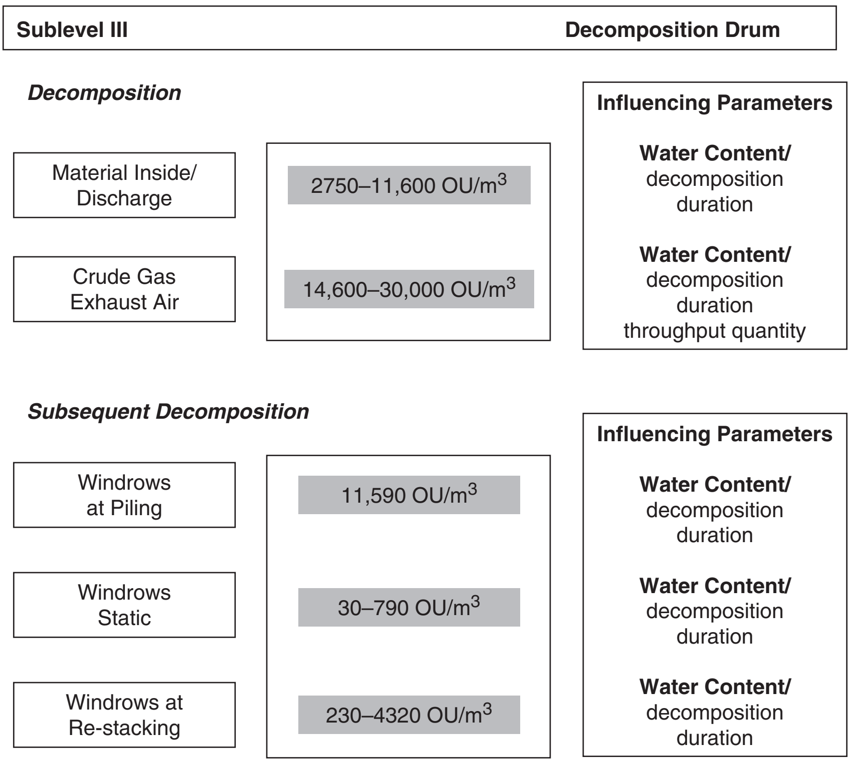
After 7 d in reactor:
at piling: 11,300 OU/m^3
static: 1 to 4 weeks 83 to 340 OU/m^3;
5 to 9 weeks 70 to 11 OU/m^3
cut up: 1 to 8 weeks 350 to 270 OU/m^3;
after re-stacking: 2 to 5 weeks 3820 to 970 OU/m^3;
7 to 8 weeks 460 to 350 OU/m^3

Basis of calculation related on 1 m^2 windrow surface:
freshly piled compost after 7 d reactor,
WC < 40%: 0.6 OU/(m^2·s);
WC > 40%: 11 OU/(m^2·s)
cut up, dry windrows, unaerated, not restacked: maximum 1.6 OU/s·m^2

Influencing parameters for sublevel II — tunnel and channel



Modular type III — decomposition drum



Sublevel III — decomposition drum

Sublevel III Parameter	**Decomposition Drum Decomposition**
Water Content	The higher the water content, the higher the odorant concentrations: **Discharge (WC 50 to 60%):** 2800 to 11,600 OU/m^3 **Discharge (WC 40 to 50%):** 2750 to 6900 OU/m^3 **Crude gas (WC 50 to 60%):** 14,600 to 27,600 OU/m^3
Decomposition Duration	Decomposition duration in the drum; **Discharge:** 1 d: 2800 to 9500 OU/m^3; 7 d: 11,600; 12 d: 7100; 14 d: 2750 to 6900 OU/m^3 **Crude gas:** 1 d: 14,600 OU/m^3; 4d: 15,500; 5 d: 23,900; 6 d: 27,600 OU/m^3
Throughput	Delivery quantity in the compost plant; up to 6500 Mg/year: 15,000 OU/m^3; 8000 Mg/year: 18,000 OU/m^3; >25,000 Mg/year: 30,000 OU/m^3

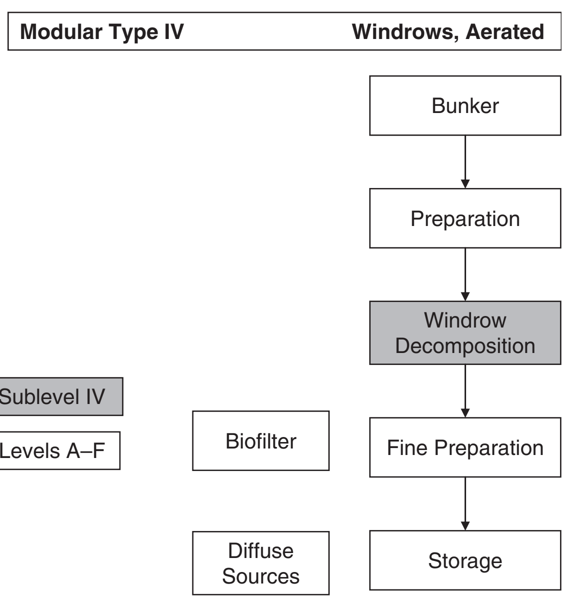
Basis of calculation related to 1 m^3 material:
at a small plant with 6500 Mg/year, 2.5 d dwell time,
delivery air 5 $m^3/m^3 \cdot h$: 21 $OU/(m^3 \cdot s)$;
at a large plant with 25,000 Mg/year, 1.5 d dwell time,
delivery air 5 $m^3/m^3 \cdot h$: 42 $OU/(m^3 \cdot s)$

Influencing parameters for sublevel III — decomposition drum

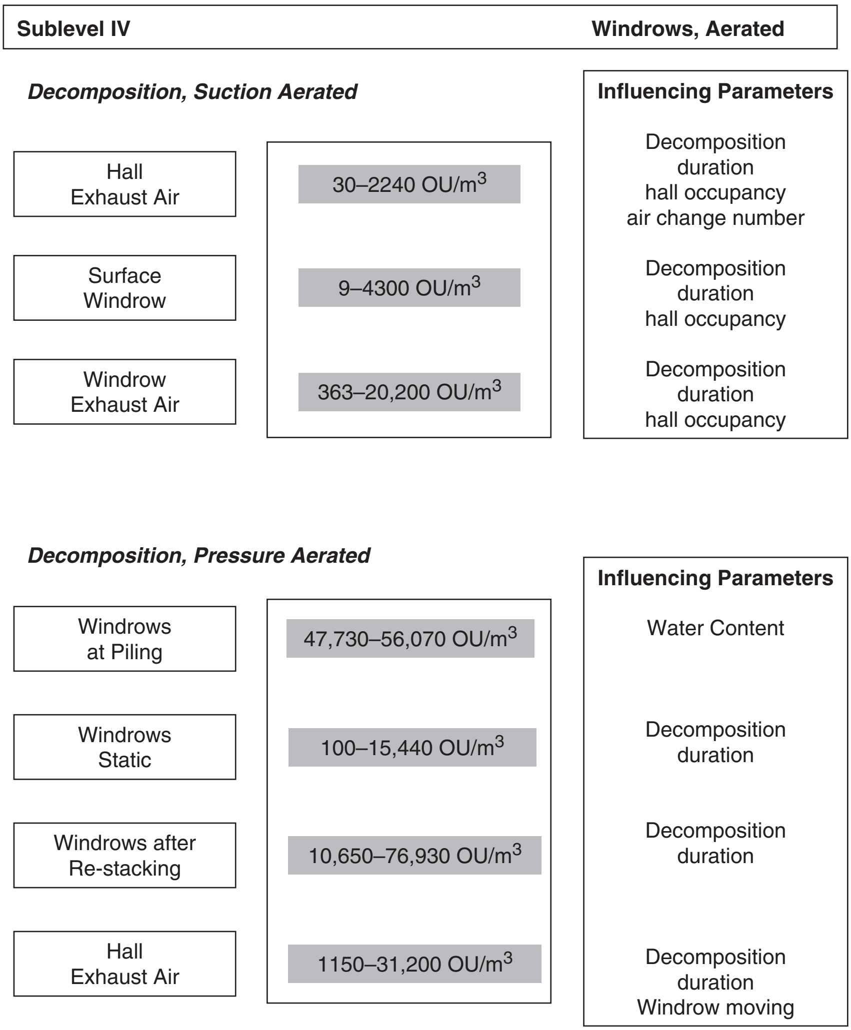
Sublevel III Parameter	Decomposition Drum Subsequent Decomposition
Water Content	The higher the water content, the higher the odorant concentrations: **Dry-humid material (WC 40 to 50%):** static: 30 to 790 OU/m^3 after re-stacking: 230 to 4320 OU/m^3 at piling: 360 OU/m^3 **Humid material (WC 50 to 60%):** at piling: up to 11,590 OU/m^3
Decomposition Duration	**After 7 d in drum:** at piling: 11,590 OU/m^3 static: 1 week 270 OU/m^3; 2 to 3 weeks 790 to 211 OU/m^3 5 to 8 weeks 90 to 30 OU/m^3; after re-stacking: 2 to 8 weeks 4320 to 230 OU/m^3

Basis of calculation related to 1 m^2 windrow surface:
cut up, dry windrows, unaerated, not re-stacked:
maximal 1.6 $OU/(m^2 \cdot s)$;
static, 7 d: 0.22 $OU/(m^2 \cdot s)$; 10 d: 0.41 $OU/(m^2 \cdot s)$; 14 d: 0.18 to 0.25 $OU/(m^2 \cdot s)$

Sublevel III — decomposition drum



Modular type IV — windrows, aerated



Sublevel IV — windrows, aerated

Sublevel IV Parameter	Windrows, Aerated Decomposition, suction aerated
Decomposition Duration	**Windrow surface:** max. 10 d: 90 to 4300 OU/m^3 max. 20 d: 67 to 2530 OU/m^3 max. 30 d: 88 to 2080 OU/m^3 max. 40 d: 94 to 2480 OU/m^3 max. 50 d: 60 to 560 OU/m^3 max. 65 d: 32 to 150 OU/m^3
Decomposition Duration/Hall Occupancy	**Windrow surface:** 6 to 8 d, 20% hall occupancy: 55 to 400 OU/m^3 9 to 22 d, 40% hall occupancy: 50 to 580 OU/m^3 6 to 54 d, 60% hall occupancy: 27 to 560 OU/m^3 7 to 65 d, 80% hall occupancy: 110 to 4300 OU/m^3 **Windrow exhaust air:** 6 to 8 d, 20% hall occupancy: 3150 to 5400 OU/m^3 9 to 22 d: 760 to 5570 OU/m^3 31 to 54 d: 60% hall occupancy: 363 OU/m^3 7 to 65 d, 80% hall occupancy: 640 to 20,200 OU/m^3 **Hall exhaust air:** 6 d, 20% hall occupancy: 60 OU/m^3 9 to 22 d, 40% hall occupancy: 30 to 46 OU/m^3 6 to 54 d, 60% hall occupancy: 60 to 260 OU/m^3 7 to 65 d, 80% hall occupancy: 180 to 1900 OU/m^3
Air Exchange Number	**Hall exhaust air:** air exchange number (Ae) 0.7: 1250 to 2240 Ae1.0: 1170 to 2090 OU/m^3 Ae2.0: 580 to 1040 OU/m^3

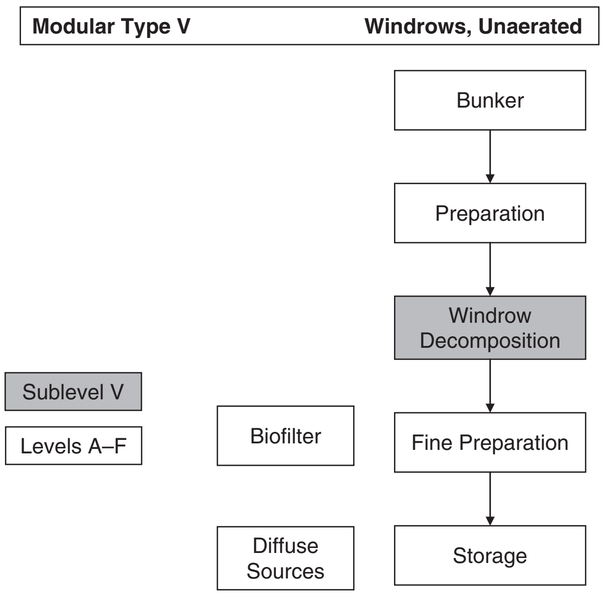
Basis of calculation related to 1 m^3 material:
hall exhaust air, suction aerated: 3 OU/($m^3 \cdot s$)

Influencing parameters for sublevel IV — windrows, aerated

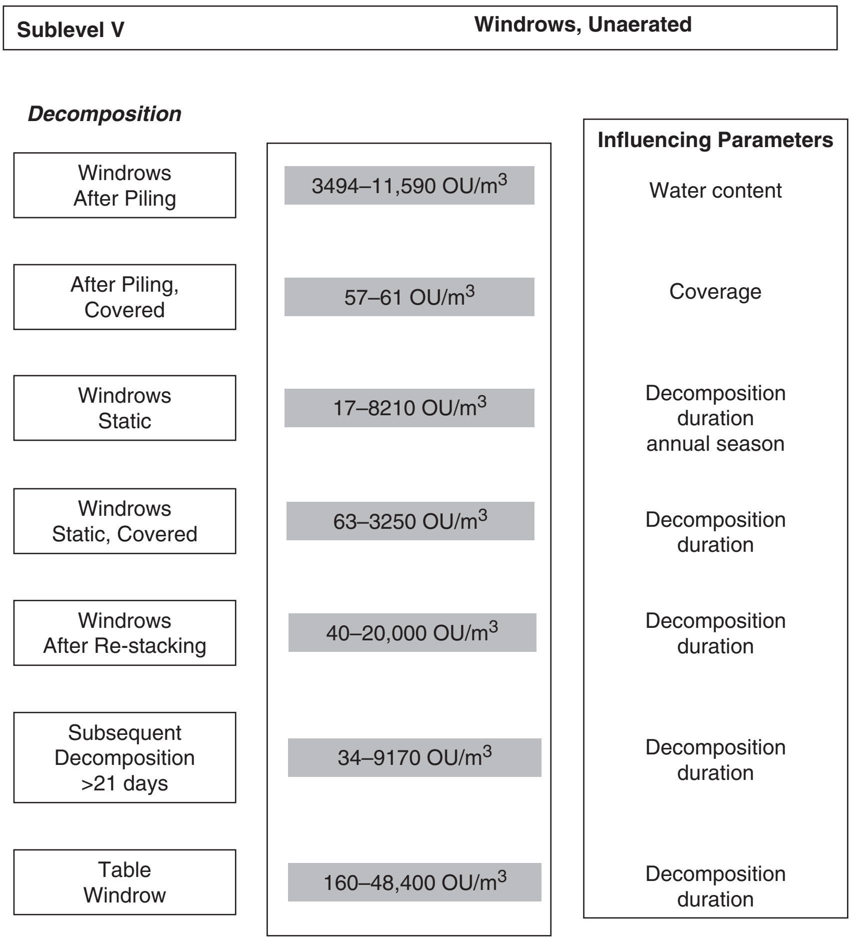
Sublevel IV Parameter	**Windrows, Aerated Decomposition, suction aerated**
Water Content	**Windrow surface, piled:** 1 d: 47,730 to 56,070 OU/m^3 **Windrow surface, static:** max. 7 d: 2420 to 4830 OU/m^3 8 to 14 d: 4960 to 3070 OU/m^3 max. 35 d: 7300 OU/m^3 36 to 77 d: 1370 to 100 OU/m^3 **Windrow surface, re-stacked:** max. 7 d: 14,600 OU/m^3 max. 14 d: 19,560 to 43,910 OU/m^3 max. 20 d: 76,930 OU/m^3 max. 28 d: 12,720 to 16,720 OU/m^3 max. 35 d: 10,650 to 25,900 OU/m^3
Decomposition Duration/ Windrow Moving	**0 to 70 d, without re-stacking:** 1150 to 5020 OU/m^3 **0 to 70 d, with re-stacking:** 22,600 to 31,200 OU/m^3 **0 to 70 d, after re-stacking:** 2470 to 4610 OU/m^3
Water Content	The higher the water content, the higher the odorant concentrations

Basis of calculation related to 1 m^3 material and single air exchange rate:
hall exhaust air, pressure aerated, static 10 OU/(m^3·s)
hall exhaust air, pressure aerated, restacked, 40 OU/(m^3·s)

Influencing parameters for sublevel IV — windrows, aerated (continued)



Modular type V — windrows, unaerated



Sublevel V — windrows, unaerated

Sublevel V **Windrows, Unaerated**
Parameter **Decomposition**

Decomposition Duration

Windrow surface, triangular windrow:
static (before re-stacking):
1 week 4320 to 8210 OU/m^3
2 weeks 52 to 2040 OU/m^3
3 weeks 27 to 420 OU/m^3
4 to 5 weeks 17 to 790 OU/m^3
6 to 8 weeks 30 to 105 OU/m^3
static, covered:
1 week 8530 to 16,870 OU/m^3
2 weeks 2810 to 10,340 OU/m^3
3 to 4 weeks 420 to 9220 OU/m^3
5 to 6 weeks 160 to 1170 OU/m^3
7 to 8 weeks 350 to 580 OU/m^3
subsequent decomposition, static:
4 weeks 17 to 790 OU/m^3
5 to 8 weeks 30 to 240 OU/m^3
subsequent decomposition, restacked:
4 weeks 480 to 2590 OU/m^3
5 to 6 weeks 160 to 1530 OU/m^3
7 to 8 weeks 350 to 580 OU/m^3
Windrow surface, table windrow:
1 to 2 weeks 1900 to 48,400 OU/m^3
3 to 7 weeks 2130 to 9170 OU/m^3
11 to 14 weeks 160 to 3740 OU/m^3

Annual Season

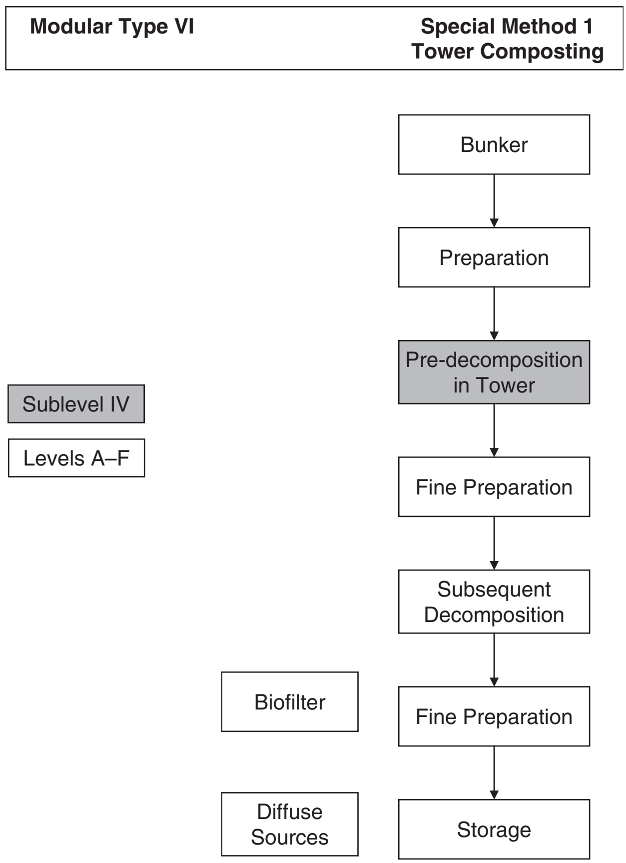
Windrow surface, triangular windrow:
summer, max. 21 d: 94 to 390 OU/m^3
winter, max. 21 d: 3520 to 5590 OU/m^3

Water Content

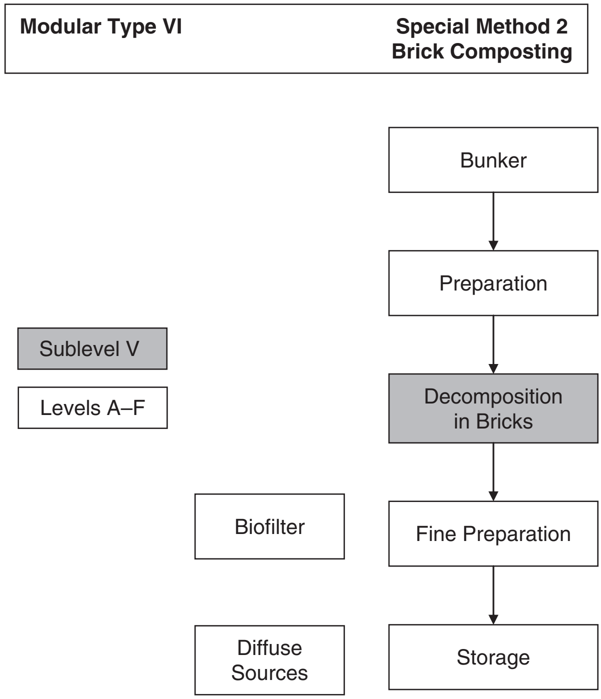
The higher the water content, the higher the odorant concentrations

Basis of calculation related to 1 m^3 material:
windrow surface after re-stacking process:
7 d 10.5 $OU/(m^3 \cdot s)$; 14 d 4.8 $OU/(m^3 \cdot s)$; 3 weeks 2.5 $OU/(m^3 \cdot s)$;
4 weeks an average of just 10% radiation after one week
surface windrow static:
7 d 6.77 $OU/(m^3 \cdot s)$; 14 d 0.66 $OU/(m^3 \cdot s)$; 3 weeks 0.16 $OU/(m^3 \cdot s)$;
9 weeks 0.06 $OU/(m^3 \cdot s)$

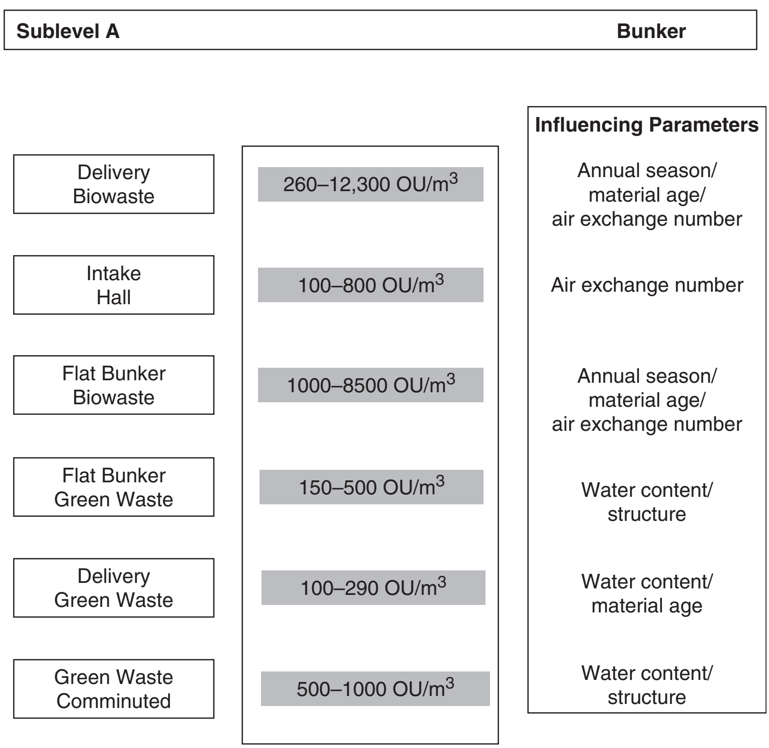
Influencing parameters for sublevel V — windrows, unaerated



Modular type VI — special method 1, tower composting



Modular type VI — special method 2, brick composting

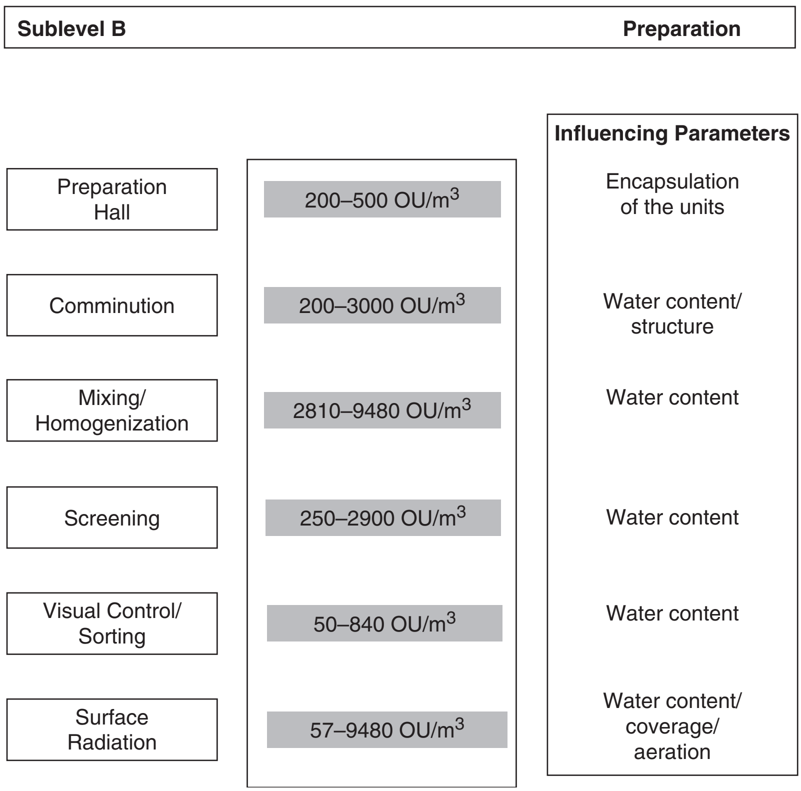


Sublevel A — bunker

Parameter	Bunker
Annual Season	Autumn: 260 to 720, winter: 630, spring: 3360 to 5470 OU/m^3; summer: 3070–8450 OU/m^3; various compositions
Material Age	Dependent on the collection frequency: the longer the standing times, the higher the odorant concentrations
Air Exchange Number	Intake hall 100 to 300 OU/m^3 at single air exchange, flat bunker biowaste with 2-fold air exchange, delivery biowaste at air exchange >1
Water Content	The higher the water content, the higher the danger of anaerobic nests with increased odorant concentrations
Structure	The coarser the structure, the better the oxygen supply and the lower the odorant concentrations

Basis of calculation related to 1 m^3 material:
small plants 6500 Mg/year: 8.5 OU/(m^3·s), max. 17
large plants 25,000 Mg/year: 3.4 OU/(m^3·s), max. 9.8

Influencing parameters — bunker

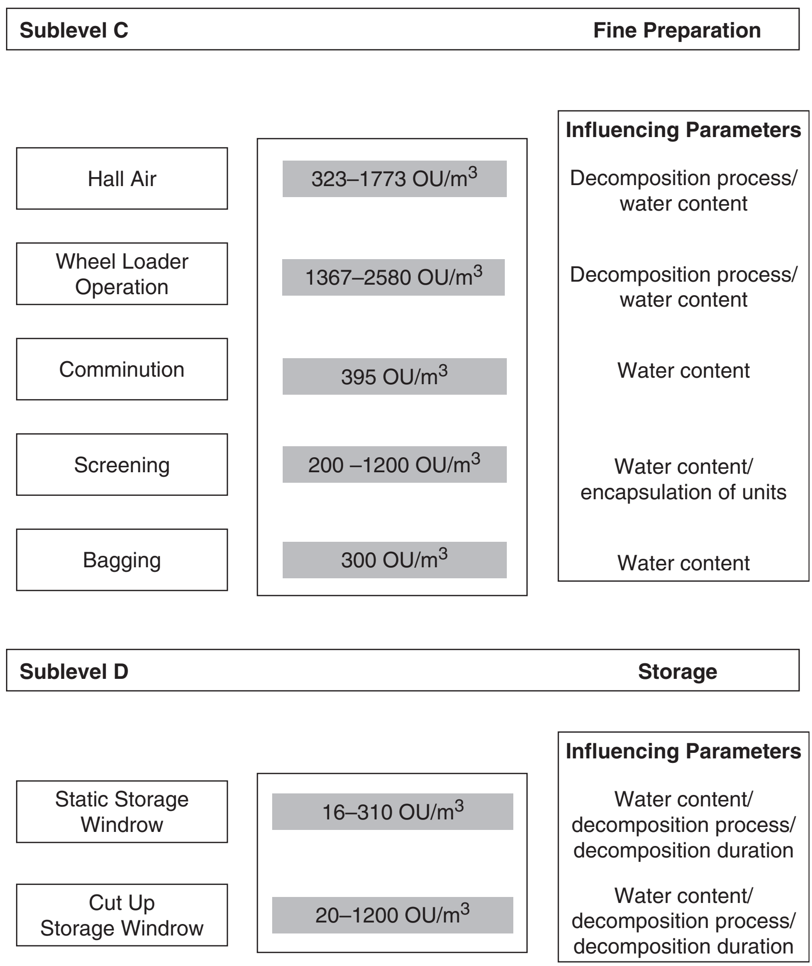


Sublevel B — preparation

Parameter	Preparation
Encapsulation of the Units	When all preparation units are encapsulated plus an air exchange number of at least 0.5, <200 OU/m^3 can be assumed in the hall
Water Content	The higher the water content, the higher the danger of anaerobic nests with increased odorant concentrations
Structure	The coarser the structure, the better the oxygen supply and the lower the odorant concentrations
Aeration/ Coverage	Freshly prepared material, unaerated, covered: 57 to 2310 OU/m^3 not covered: 1210 to 6420 OU/m^3 freshly prepared material, aerated, not covered: 6410 to 9480 OU/m^3

Basis of calculation related to 1 m^3 material:
small plants 6500 Mg/year: 10 OU/(m^3·s), max. 19
large plants 25,000 Mg/year: 3.8 OU/(m^3·s), max. 7.2
(samples taken at the surface of the prepared material, directly after preparation)
related to 1 m^3 surface: 4.12 OU/(m^3·s) mean value

Influencing parameters — preparation



Sublevel C — fine preparation

Parameter	Fine Preparation
Encapsulation of the Units	By encapsulation of the screen unit, a hall air load of <50 OU/m^3 of a screening station can be assumed, dependent on air exchange rate
Decomposition Process	An optimal decomposition process (optimal water content, no anaerobic parts) can realize a surface radiation of the compost of <500 OU/m^3; a non-optimal decomposition has hall air values of 1773 OU/m^3 without and up to 2580 OU/m^3 with wheel loader operation
Water Content	A high water content is proof for a non-optimal decomposition process; thus, the values of the decomposition process are valid

Influencing parameters — preparation

Parameter	Storage
Decomposition Process and Duration	At an optimal decomposition process (optimal water content, no anaerobics, decomposition degree III), a mean value of 80 OU/m^3 is reached in static storage windrows; cut up windrows reach a mean value of 250 OU/m^3; a non-optimal decomposition reaches up to 1200 OU/m^3
Water Content	A high water content is proof for a non-optimal decomposition process; thus, the values of the decomposition process are valid

Basis of calculation related to 1 m^3 material:
static storage windrows:
small plants 6500 Mg/year: 0.17 OU/(m^3·s), max. 0.42
large plants 25,000 Mg/year: 0.07 OU/(m^3·s), max. 0.18
the values rise by a factor of 3.1, maximal by 5.5 at cut up windrows

Influencing parameters — storage

Sublevel E		**Biofilter**
		Influencing Parameters
Crude Gas	129–2000 OU/m^3	Plant operation
Clean Gas	16–250 OU/m^3	Maintenance/ operation

Sublevel F		**Diffuse Sources**
		Influencing Parameter
Traffic Areas	20–200 OU/m^3	Soiling

Sublevel E — biofilter

Parameter	**Biofilter**
Operation and Maintenance	Efficiency of 85 to 95% can be achieved with a proper operation of the plant and a continuous controlling of the filters

Basis of calculation related to 1 m^2 surface: inherent smelling of the biofilter

Parameter	**Diffuse Sources**
Soiling	The degree of soiling the traffic routes increases the portion of diffuse odorant concentrations outside the buildings

Additional safety charge of 10% of the definite emissions for diffuse sources

Influencing parameters — biofilter

Chapter 12

Marketing of Composts

L.L. Eggerth, L.F. Diaz, M.T.F. Chang, and L. Iseppi

12.1. Introduction

The financial feasibility of a program designed to recover resources from municipal solid wastes is, to a large extent, a function of the availability, reliability, and location of markets for the materials that are recovered. Obtaining markets for compost accomplishes one primary objective: it provides end uses for the finished product. In addition, the availability of markets provides an important source of revenue, defrays some of the cost of processing, and contributes to the financial viability of an overall waste management strategy. The latter is an important consideration in reducing the amount of residues that are disposed on the land.

12.2. Markets for Compost

12.2.1. Importance of Product Quality

Compost has the potential to be used as a soil amendment in various applications. Compost can substantially improve the fertility, texture, aeration, nutrient content, and water retention capacity of the soil.

Due to its beneficial characteristics, compost has a variety of potential applications and can be used by several market segments. Some of the markets include:

- agriculture (small- and large-scale);
- landscaping;
- gardening (residential, community);
- nurseries;
- top dressing (e.g., golf courses, parks, median strips);
- land reclamation or rehabilitation (landfills, surface mines, and others); and
- erosion control.

The markets or uses listed in the previous paragraph are constrained by: (1) the characteristics of the compost, (2) the limitations applicable to its use, and (3) pertinent laws and regulations (Alexander, 2000; Harrison et al., 2003).

Results of marketing studies and surveys conducted in several countries have demonstrated that some of the most critical elements in the use and marketability of the compost products are: (1) quality, and (2) consistency. The quality of a specific type of compost is a function of its chemical, biological, and physical characteristics. Assuming that a composting process is properly carried out, the quality of the finished product is determined by: (1) the composition and characteristics of the input material used in the production of the compost, and (2) the type and thoroughness of the process used to remove impurities.

Some of the physical characteristics that are normally desired for a particular compost product are color, uniform particle size, earthy odor, absence of contaminants, adequate moisture, concentration of nutrients, and amount of organic matter (Eggerth et al., 1989; Eggerth and Diaz, 1992). Each of these characteristics is discussed in the following sections.

12.2.1.1. Color

As the composting process advances, it generally results in a natural darkening in the color of the material being composted. For example, the organic fraction of municipal solid waste changes from grayish-green to black. A deep, dark material is popularly associated with stability, maturity, and a high concentration of organic matter.

12.2.1.2. Particle Size

The size distribution of soil amendments plays a very important role in the storage, packaging, distribution, and final use of the material. Furthermore, the size distribution of the individual particles that make up a certain type of soil determines the texture and therefore has an impact on the productivity of the soil. Texture defines porosity, permeability, and other factors that are important for plant growth.

12.2.1.3. Odor

Odor is a relatively simple but very practical method of monitoring the status of the composting process. The presence of unpleasant odors during the composting process generally is an indication that anaerobic conditions have been established. The continuous presence of a strong earthy odor is a good (but not definitive) indication that the compost process is completed. In the process of selecting a compost, expert users of organic soil amendments look for the presence of a strong earthy odor.

12.2.1.4. Contaminants

The compost ready for market should not contain identifiable contaminants such as rocks, glass particles, and relatively large pieces of metal and plastics. In addition, the material should not contain harmful concentrations of weed seeds, heavy metals, toxic compounds, or pathogens.

12.2.1.5. Moisture Content

In most situations, the moisture content of the finished compost should be less than 50% to promote ease of handling, transport, and application. On the other hand, if the compost is excessively dry (less than about 30% moisture content), the condition could mask the degree of stability of the product.

12.2.1.6. Nutrient Content

The concentration of nutrients in compost made from the organic fraction of municipal solid waste (MSW) is usually relatively low (generally, the NPK is between 1 and 1.5). On the other hand, the nutrients in the compost are in a form that can be used by plants. Some of the most important plant nutrients include nitrogen, phosphorus, and potassium. Minor nutrients include copper, manganese, iron, and boron. However, nutrient content is not the only indicator of the utility and value of the product.

12.2.1.7. Organic Matter

The real utility of compost is its ability to increase the concentration of humus in the soil. Humus enhances the friability and water-holding capacity of soil.

At the present time, there is a concerted effort toward improving the quality of compost by controlling the feedstock and the process. Compost that is produced from source-separated organic materials (e.g., yard waste, food waste, biowaste) generally has a higher and more consistent quality than compost produced from mixed residues, primarily due to a smaller concentration of contaminants. In fact, in the EU, the material that is produced by composting mixed MSW is not considered compost.

In addition to these characteristics, producers and users of the material also consider: salt concentration, stability/maturity, and feedstock materials (Hudson, 2000). Other important parameters include: pH, C/N, bulk density, and certifications. A summary of parameters that may be used to define compost quality is presented in Table 12.1.

12.2.2. Potential Markets

The size of a particular market for compost depends, to a large extent, on the quality of the compost and on the types of uses for the material. Composts from different types of substrates (e.g., yard waste, source-separated MSW) have different characteristics and consequently have different potential markets (Franklin Associates et al., 1990).

12.2.2.1. Compost from the Organic Fraction of MSW

Agriculture

The agricultural industry (either small- or large-scale) is the largest potential market for compost, particularly compost produced from the organic fraction of MSW. There are two main reasons for this situation: (1) the nature and quality of MSW compost, and (2) the relatively large quantities of substrate that would be available if composting were widely used as a means of treating the organic fraction of MSW. Land reclamation and rehabilitation rank next in potential size of market.

Studies have shown that the continuous application of compost on the soil has beneficial effects that include favorable pH, higher crop yields, increased concentration of organic

Table 12.1. Parameters that may be used to define the quality of compost

Category	Parameter	Purpose
Physical	Bulk density	Transportation, handling (e.g., application), storage
	Color	Aesthetics
	Moisture content	Handling
	Odor	Health, environment, aesthetics, marketability
	Organic matter content	Soil quality
	PH	Soil quality
	Size distribution	Handling, aesthetics, soil quality
	Water-holding capacity	Soil quality, water conservation
	Contaminants (inert matter)	Public and animal health, soil quality, environment, aesthetics
	Maturity	Soil quality, crop production, stability
Chemical	Nutrients (macro and micro)	Soil quality, crop production
	Heavy metals	Soil quality, health, environment
	Soluble salts	Soil quality, crop production, environment
Organic	Toxic compounds	Health, environment
Biological	Pathogens	Health, environment
	Seed germination	Soil quality
	Weed seeds	Soil quality, crop production

Source: CalRecovery, 1993.

matter, increased cationic exchange capacity, enhanced supply of plant nutrients, and increased water retention (Mays and Giodano, 1989).

Developments in agriculture have increased the recognition of the utility of compost. One of the developments is that associated with an increasing understanding of the consequences of the loss of topsoil due to erosion, particularly the reduction in soil fertility (Schertz, 1988). Erosion of the topsoil is caused to a large extent by the reduction in the concentration of organic matter in the soil. The recognition that the organic matter lost through erosion can be replaced by an organic soil amendment such as compost is stimulating the market for compost and other organic soil amendments (USDA, 1978).

Another beneficial effect that can make an important impact in the development of a market for soil amendments in small- and large-scale agriculture is the reduction of solubility of inorganic fertilizing elements (such as N, P, and K) due to the presence of organic matter. The conversion of highly soluble inorganic fertilizer elements to slowly soluble organic forms leads to an increase in the efficiency of the use of nutrients by crops.

The competition between compost and chemical fertilizers has started to decrease, and the two products are now viewed as being complementary rather than competitive. This change in attitude is due to the growing recognition of the importance of the following facts: (1) the presence of organic matter in soil increases the efficiency of the use of chemical fertilizer in crop production, (2) compost can serve as a supplement rather than a competing source of NPK, (3) compost increases the concentration of organic matter in the soil and thereby enhances the water retention capacity of the soil, and (4) the cost of inorganic fertilizers is increasing (USDA, 1978; Schertz, 1988; Alexander et al., 2004).

In addition, the continuous increase in demand for organically grown foods throughout North America and Western Europe has had a very positive effect on the need for organic soil amendments.

Unfortunately, large-scale agriculture is still a difficult market to penetrate. Some of the factors that must be addressed in order to develop this market are: availability of compost at the time when it can be applied to the soil, consistency in composition and nutrient content, insuring low levels of toxic substances, procedures for bulk application, and acceptance by farmers.

The following classification of agriculture is useful for evaluating the market potential of the compost product: field crops, row crops, orchard, and horticultural.

Field Crops Due to the large amount of land area devoted to field crops, it would be expected that field crop agriculture would provide a very important market for compost from biowaste. However, because of the difficulties associated with the application of compost in comparison with competing products, the actual size of the market is still relatively small. Compost from biowaste competes poorly with chemical fertilizers because the bulk density and NPK content of the compost are substantially lower than those of chemical fertilizers. Bulk densities of compost produced from biowaste range from about 420 to 590 kg/m^3 and, consequently, relatively large quantities of the product must be applied. Therefore, to apply a certain amount of NPK to a field crop, the quantity of chemical fertilizer is measured in terms of kilograms per hectare, whereas with compost it would be measured in tons per hectare. Many farmers regard the relatively large amounts of compost involved as an important disadvantage because of the associated increase in costs due to transport and application.

The reluctance to use compost in field crop agriculture is further complicated by the fact that the material is generally not available on a continuous basis. The lack of availability is a negative factor because it is very difficult to develop a market without a reliable and sufficiently large supply of a consistent product.

Row Crops, Orchards, and Ornamentals The market for compost in row crop and orchard agriculture and ornamentals has not reached its full potential. This is mostly due to an unfortunate combination of limited supply of high-quality compost and the price demanded for the product. This situation is bound to change due to the implementation of requirements to divert organic matter from landfills.

Land Reclamation

The market for compost in land reclamation is substantially different from the agricultural market because land reclamation is usually a responsibility of the public sector. On the other hand, agriculture in most cases is controlled by the private sector. Consequently, purchasing compost and other soil amendments for land reclamation is normally done by government agencies. Regardless of whether the government produces the compost or purchases it from a private producer, the potential demand always will be large. The financial aspects of the market depend on the government's willingness to pay for the compost required.

12.2.2.2. Compost from Yard Waste

Several marketing analyses for composted yard waste may be found in the literature. However, most of the surveys merely explore and identify potential markets for the compost. Many surveys are flawed by a lack of a thorough understanding of the characteristics of the compost product.

Results of market surveys carried out by the authors show that the organizations or individuals who typically express the most interest in using yard waste compost are:

- home gardeners;
- landscape contractors and suppliers;
- sod and sodding services;
- retailers of soil conditioners;
- nurseries; and
- public agencies.

Usually, most landscape contractors, sod and sodding services, and retailers of soil amendments buy compost or other soil amendments in relatively large quantities. Most businesses generally express preferences for certain specifications for the compost and the need for consistency in the quality of products is frequently mentioned. Other specifications that are important to businesses are: nutrient content; potential contamination with pathogens, heavy metals, and toxic compounds; appearance of the compost; purchasing convenience; and availability.

Public agencies have the potential to use both high- and low-quality composts. High-quality compost can be used in areas where humans and/or animals may come in direct contact with the materials. Lower quality compost would be suitable for land reclamation and filling. Examples of potential uses by public agencies include: parks and redevelopment, weed control on public lands, land reclamation and upgrade, landscaping of the median strip, and roadway maintenance. Other markets that are experiencing some growth include: erosion control, stormwater management, and bioremediation.

The residential sector also represents a sizeable market for soil amendments. Results of marketing surveys conducted by the authors and their colleagues show that a large number of people expressed a preference to use compost from yard waste than from the organic fraction of MSW or from biosolids. This preference largely stems from concerns related to health and safety. In order to successfully market compost to the residential sector, the public needs to be assured of product safety and be well informed on the possible uses of compost.

Some of the difficulties facing the marketing of compost deal with: consumer acceptability, the lack of public education, and biases toward certain feedstocks (Alexander, 2000).

12.2.3. Purchase Considerations

Compost is sold in bulk or bagged form. Preferences depend upon the quantities used. Large-scale users such as landscape contractors, nurseries, farmers, and park districts usually prefer to buy compost in bulk (in large quantities and not bagged). On the other hand, small-scale users such as home gardeners often prefer the bagged form. Sizes of bagged compost usually range from about 0.03 to 0.06 m^3, although there are some bagged products that are larger than that. Bagged compost is frequently purchased through nurseries and garden supply stores.

At the present time in the United States, most compost made from the organic fraction of MSW and from yard waste is marketed in bulk form at no cost or a relatively low cost. The major portion of biowaste compost is given away for free; some of the compost is sold for \$5–10/m^3. High-quality yard waste compost sells in bulk for between about \$14 and \$16/m^3. In some instances, the yard waste compost and compost from biosolids are bagged and sold for the equivalent of \$28/m^3 or more (all prices are in 2005 US dollars). In the United States, wholesale prices for compost freight-on-board (FOB the facility) vary between about \$2 and \$20/m^3. On the other hand, retail prices (FOB the facility) fluctuate between about \$5 and \$25/m^3 (Alexander, 2000).

12.2.4. Competitive Products

There are several organic residues that can be competitive with compost produced from the organic fraction of MSW and from yard waste for the soil amendment market. The size of the entire amendment market varies substantially from country to country and from community to community. Type and quantity of each of the marketed amendments depend upon the geographic location. In addition to compost, soil amendments that are currently used include: bark, manure, peat moss, perlite, sawdust, straw, and woodchips (Robinson and Lamb, 1975).

In addition to compost made from biowaste, several types and grades of composts are currently being produced. Among the composts that would compete with biowaste compost are those produced from other urban residues such as biosolids and yard debris. Other residues currently in use include animal manures, bark and sawdust, spent mushroom compost, and leaves. Many of the compost producers and sellers are making excellent blends of two or more materials, which are made specifically for certain uses.

12.3. Limitations on Use of the Compost Product

Limitations on the use of the finished compost are related to the possible adverse effects on: (1) human health and safety; (2) animal (livestock) health and safety; (3) crop production; and (4) the quality of the air, water, and land resources. The importance of each limitation depends upon whom or what is affected and the extent to which they are affected.

The limitations associated with the use of the compost with respect to the health and safety of humans are related to the harmful substances that may be present in the product. Examples of such substances are pathogenic organisms, heavy metals, glass, PCBs, and other toxic organic compounds. The waste used as feedstock for the compost process is the source of harmful substances that may appear in the product. Although the output from processing mixed MSW is not considered compost in countries that are members of the EU, this practice is still being conducted and considered in other countries.

During the last fifty or so years, the composting of wastes usually involved the use of biosolids as the feedstock; a substantial amount of the available literature deals with composted biosolids (Gotaas, 1956; Golueke, 1977). Concentrations of pathogens and heavy metals are usually higher in sludges than in the organic fraction of MSWs, as is shown by the data in Table 12.2. When considering the data, it should be kept in mind that concentrations vary widely from operation to operation due to a variety of site-specific differences, e.g., mostly residential (domestic) versus mostly industrial generators. Increasingly stricter regulations regarding the concentrations of objectionable substances will gradually lower the concentrations of those substances in industrial sludge. Regarding municipal wastes, PCBs have been found in them (Cal Recovery Systems, 1988; CalRecovery, 1990). However, the reports are too fragmentary to indicate trends.

12.3.1. Toxic Substances

At present, reliable information on concentrations of toxic substances and pathogens in composted yard debris is scarce. The few available data indicate that heavy metal concentrations are very low (<1 ppm each of Cd, Hg, Cd, and about 72 ppm of Pb). Concentrations of pesticides, PCBs, and pathogens are at or below limits of detection (Cal Recovery Systems, 1988; CalRecovery, 1990).

The information presented in the preceding paragraphs can be used to conclude that compost products, especially those made from MSW and biosolids, should be routinely analyzed as a precautionary measure.

The harmful effect on humans and on animals may be exerted directly by eating food crops grown on soils that received compost. The effect can also be exerted indirectly through the consumption of meat and other products involving animals fed on such crops. The effects are due to: (1) persistence of inorganic contaminants and (2) survival of certain pathogens through the food chain.

Cadmium can be used to demonstrate how a heavy metal “moves” through the food chain. A certain amount of cadmium present in the soil is taken up by plants growing on the soil. The specific amount that is assimilated by the plant is a function of several factors. Some of the factors include: the availability of the metal, type of plant, and the particular part of the plant (e.g., root, leaf, and fruit). The characteristics of the soil that have an impact on the availability of a particular metal are: concentrations of the metal, amount of organic matter, pH, ion exchange capacity, moisture content, and others. With regard to the pH of the soil, availability of a metal usually decreases as the soil pH increases (i.e., becomes more alkaline). Generally, leafy vegetables assimilate more metals than

Table 12.2. Characteristics of different types of compost

	Unit[a]	Yard waste	Wastepaper[b]	Food waste[c]	Mixed MSW
Physical					
Bulk density	kg/m^3	306–404	327[a]	356[a]	356–475[a]
CEC	mS	0.8–4.07			
Moisture content	%	34–61	~40	~40	~45
pH		5.8–7.2			
Size distribution	nominal cm	2.8–10[d]	2.5–10[e]	<1.9[e]	2.5–10[e]
Water-holding capacity	%	110–300			
Chemical					
Aluminum	ppm	600			
Arsenic	ppm	5.0	54.6	1.8	1.1–9
Boron	ppm	0.5–81	24.4	3.8	
Cadmium	ppm	0.8	1.2	0–0.8	1.4–6.0
Calcium	ppm	875	2800	2511–38,400	
Carbon (total)	%	32.5	17.8	7.3	
Chlorine	ppm	192			
Chromium	ppm	23	27.1	6.6–23.8	16.2–220
Cobalt	ppm		7.0	1.8–17.2	
Copper	ppm	2–6	61.6	8.7–24.8	46.5–630
Cyanide	ppm				0.49
Iron	ppm	144–412	2945	922	
Kjeldahl nitrogen	%	0.7	0.53	0.95	
Lead	ppm	72	82.4	7.5–23.8	82.4–913
Magnesium	ppm	11–920	3100	1050–9000	
Manganese	ppm	36	64.2	21–181.6	
Mercury	ppm	0.06	0.02	0.01	1.2–5.0
Molybdenum	ppm		16.3	9.2	
Nickel	ppm	22	18.4	2.1–2.9	8.3–110
Nitrates	ppm	2–8			
Phosphorus	ppm	4–280	640	1300–4600	
Potassium	ppm	184–3600	3100	5800–8900	
Sodium	ppm	39–753			
Soluble salts	mS	0.7–1.9			
Zinc	ppm	19–160	142	24.7–110.2	266–1650
Organic					
2,4,5-T	ppm	<0.5			
Aldrin	ppm	0.007			ND to 0.07
Casoron	ppm	Present			ND
Chlordane	ppm	0.15–0.32			ND
Dalapon	ppm	<0.5			ND
Diazinon	ppm	ND			
Dicamba	ppm	0.5–12.9			
Dichloroprop	ppm	<0.5–1.2			

Table 12.2. Characteristics of different types of compost — *Cont'd*

	Unit[a]	Yard waste	Wastepaper[b]	Food waste[c]	Mixed MSW
Dieldrin	ppm	0.019			0.04–0.08
Dinoseb	ppm	<0.5–1.0			
Dursban	ppm	0.039			ND
Endrin	ppm	ND			ND
Lindane	ppm	ND			0.08
Malathion	ppm	ND			ND
MCPA	ppm	<0.5–1.2			
MCPD	ppm	<0.5–7.1			
o, *p*, DDT	ppm	0.004			
p, *p*, DDE	ppm	0.005–0.014			ND
p, *p*, DDT	ppm	0.008–0.019			ND
Parathion	ppm	ND			ND
PCBs	ppm	ND			0.32–2.53
PCPs	ppm	0.12–0.21			0.016
Silvex	ppm	<0.5			
Trifluralin	ppm	Present			ND
Biological					
A. fumigatus		Negative			Negative
Ascaris lumbr.		Negative			Negative
Coliform (total)	MPN/100 ml	$1.4–300 \times 10^3$			4.0×10^8
Dog parasitic ova		Negative			Negative
E. coli	MPN/100 ml	$<1.0 \times 10^4$			$>1.1 \times 10^8$
Fecal coliform	MPN/100 ml	$2.3–93 \times 10^3$			$>1.1 \times 10^8$
Human parasitic ova		Negative			Negative
Pseudomonas spp.		Positive			Positive
Salmonella sp.		Negative			Negative
Taenia sp.		Negative			Negative
Trichuris trichuria (hookworm)		Negative			Negative

[a]Dry weight basis.
[b]Calculated.
[c]Limited available data supplemented by calculated values.
[d]Visual.
[e]Estimated.
Source: Diaz et al., 1993

cereal crops. In cereal crops, the concentration of metals is greater in the root and in the leafy portion of the plant than in the grain. If any of those plants are eaten by humans, a certain amount of the cadmium or other metal in the plants is assimilated in the tissues of the persons who eat the plants. If the plants that contain the heavy metals are consumed by animals, a certain amount of each metal is assimilated by the animals and remains in their tissue and in the products (e.g., eggs) produced by them. The relative size of the fraction depends upon the type of metal. Finally, individuals who consume the meat or the products of the animals assimilate a fraction of the metals in the meat and products. The distribution of cadmium in the soil, plant, and animal as it passes through the food chain, and the contribution of biosolids, are described in detail in Mennear (1978); Sharma (1980); Chaney (1982); and Golueke (1982). The incidence of other metals and chemicals in the food chain are summarized in Cal Recovery Systems (1988).

12.3.2. Pathogens

The limitations that come about from the presence of pathogens in compost fluctuate from very small to substantial, depending upon the type of waste that is composted and the conditions under which the material was processed and was composted. Pasteurizing removes the constraints. Pasteurization can be accomplished by the composting process itself or through the application of an external source of heat prior to composting as it is required in some countries in Western Europe. Except through contamination by contact (e.g., adhering compost particles); direct transfer of pathogenic organisms between members of the food chain even without disinfection is either non-existent or very minor.

The types and concentrations of pathogens that might be found in the compost prior to pasteurization depend upon the feedstock. Yard wastes are not likely to contain human pathogens because human body wastes are not involved. However, yard wastes may contain organisms pathogenic to pets or to plants. Biosolids, on the other hand, have a wide range of human pathogens. MSW may contain some human pathogens because of contamination by body wastes. The microorganisms that are normally used to indicate the potential presence of body wastes of man and animal origin are similar; consequently, the degree, if any, of contamination with human body waste cannot be measured by concentration of "indicator organisms" (Cooper et al., 1974; Diaz et al., 1977). In fact, the concentration of the indicators in yard waste from areas that have a sizeable pet population may rival that in biosolids. Improperly composted food wastes could contain zoonotic organisms (trichina, ascaris, taenia) by way of meat scraps. In summary, composted yard waste is not likely to contain human pathogens, whereas inadequately composted biosolids and food waste could do so. Furthermore, composted food waste could contain other organisms that have caused several problems with animal populations, primarily in Western Europe.

12.3.3. Regulatory

Health constraints are receiving legal support by way of "classifications" proposed or actually promulgated by the U.S. EPA and various state regulatory bodies in the U.S. and by several countries in the EU. However, composts made from yard waste and from agricultural residues have been and are being less closely regulated (Harrison et al., 2003). Classifications based on heavy metal content are presented in Table 12.3. The data are examples only of classifications either in existence or proposed as of 2004.

Table 12.3. Examples of U.S. state regulations for compost

Classification/ feedstocks	New York Class I yard debris MSW/sludge	Minnesota Class I MSW	Florida Code 1 yard debris MSW/sludge	Maine Class A MSW/sludge
Heavy metals (ppm)				
Cadmium	10	10	< 15	10
Lead	250	500	< 500	700
Mercury	10	5		10
Zinc	2500	1000	<900	2000
Chromium	1000	1000		1000
Nickel	200	100	<50	200
Copper	1000	500	<450	1000
Organic compounds				
PCBs (ppm)	<1	<1		<10
Dioxin (ppt)				
Food				<27
Nonfood				<27–250
Physical properties				
Moisture content (%)		50–60		
Odor		Control		
pH			5.0–8.0	
Particle size (mm)	<10	<25	<10	
Biological properties				
Human pathogens		Minimized		

Source: Diaz et al., 1993.

In the United States, labeling is an important legal constraint that is not oriented to health. It prohibits use of the term "fertilizer" in the label of a compost product that has a combined concentration of nitrogen, phosphorus, and potassium (NPK) lower than 6% (the required total may vary from state to state). The types of labels that are permitted are "soil amendment," "soil conditioner," or simply "compost." The NPK of a compost product is a function of the NPK of the wastes from which the compost is produced. Because of the wide variations between products in terms of nutrient content, it would be misleading to list particular concentrations as being "typical." Nitrogen content and C/N of a number of organic materials and wastes are listed in Table 12.4. It has become clear that in the United States and in several other countries, there is a need to develop consistent, easy-to-read labels in order to provide assistance to the consumer in comparing materials and selecting those that meet their needs (Harrison et al., 2003).

Table 12.4. Approximate nitrogen content and C/N ratios of some compostable materials (dry basis)

Material	Nitrogen content (%)	Carbon-to-nitrogen ratio
Urine	15–18	0.8
Blood	10–14	3
Fish scrap	6.5–10	–
Poultry manure	6.3	–
Mixed slaughterhouse waste	7–10	2
Nightsoil	5.5–6.5	6–10
Activated sludge	5.0–6.0	6
Meat scraps	5.1	–
Purslane	4.5	8
Young grass clippings	4.0	12
Sheep manure	3.75	–
Pig manure	3.75	–
Amaranthus	3.6	11
Lettuce	3.7	–
Cabbage	3.6	12
Tomato	3.3	12
Tobacco	3.0	13
Onion	2.65	15
Pepper	2.6	15
Cocksfoot	2.55	19
Lucerne	2.4–3.0	16–20
Kentucky blue grass	2.4	19
Grass clippings (average mixed)	2.4	19
Horse manure	2.3	–
Turnip tops	2.3	19
Buttercup	2.2	23
Raw garbage	2.15	25
Ragwort	2.15	21
Farmyard manure (average)	2.15	14
Bread	2.10	–
Seaweed	1.9	19
Red clover	1.8	27
Cow manure	1.7	–
Wheat flour	1.7	–
Whole carrot	1.6	27
Mustard	1.5	26
Potato tops	1.5	25
Fern	1.15	43
Combined refuse, Berkeley, CA (average)	1.05	34
Oat straw	1.05	48
Whole turnip	1.0	44
Flax waste (phormium)	0.95	58
Timothy	0.85	58

Table 12.4. Approximate nitrogen content and C/N ratios of some compostable materials (dry basis) — *Cont'd*

Material	Nitrogen content (%)	Carbon-to-nitrogen ratio
Brown top	0.85	55
Wheat straw	0.3	128
Rotten sawdust	0.25	208
Raw sawdust	0.11	511
Bread wrapper	Nil	–
Newspaper	Nil	–
Kraft paper	Nil	–

Source: Gotaas, 1956.

12.4. Market Development

The results of several marketing studies of organic soil amendments produced from various types of municipal wastes have demonstrated that the development of a market is, to a large extent, a matter of overcoming inertia and bias, and instilling awareness in potential users (Alexander, 2000). This can be accomplished by means of a comprehensive program of education and salesmanship (Tyler, 2001). The task is made easier by the fact that the product has a genuine utility. All that remains is for the potential market to recognize the utility.

12.4.1. Market Analysis

The development of a market should begin with a statistically reliable survey designed to: (1) find the full size of the market potential, (2) determine the steps to be followed, and (3) identify and elaborate the best method of carrying out the steps. The analysis should be conducted through personal interviews and/or questionnaires in order to determine the needs and potential of the prospective users. In the interviews, it should be remembered that knowledge of the customer's values and motivations is a necessary condition in the sale of a product.

Interviews should be conducted with representatives of groups that are potential users of the product. Among these groups are the major agricultural sectors, government agencies, landscape contractors, soil vendors and distributors, nurseries, and the general public. When conducting the desired number of personal interviews is not possible and if it is appropriate to do so, personal interviews can be supplemented by mailed questionnaires. Generally, it is advisable that the questionnaires be designed such that they are concise and easily understood.

Questions should be adapted to the market under evaluation. Thus, information to be collected from the agricultural sector should concern types of crops grown by the interviewee, amounts of NPK used, times of the year when nutrients are applied, type of soil, and amount of organic matter in the soil. Other information would pertain to size and ownership of the land.

12.4.2. Educational Activity

Once the size of the potential market has been estimated, it should be followed by the development of a plan to make the market materialize. Attainment and extent of the materialization depend in part upon the effectiveness of the sales force used to market the compost. A part that is equally important involves the establishment of a receptive "climate" by convincing the general public of the utility of using compost.

Instilling awareness in the public should be the first step in a geographical area where a market for compost either is non-existent or is very small. Public education is an excellent mechanism for accomplishing that step. The education can be carried out by way of presentations in the media (publications, radio, and television). The presentations should address the advantages and disadvantages of using compost, methods of producing compost, information on obtaining compost, and proper application and utilization of compost.

Education of the public should be followed or complemented by the education of the potential users of the product. For example, this can be done by addressing farm and urban groups. These presentations should include demonstrations regarding the best use of the product for particular applications.

As a part of the implementation of the educational and promotional programs, efforts should be made to enlist the services of governmental and educational specialists who understand and work with the particular market segments on a local scale. Because of their close association with the market segments, their advice is more likely to be accepted.

12.4.2.1. Case 1

An educational program was proposed for a farmers' cooperative and is a useful model. The proposed approach was based on a program designed for the introduction of an innovation. As proposed for the cooperative, the program required persuading a local leader or a farmer who is highly esteemed by his fellow farmers to test the compost product on his farm. Convincing a leader regarding the use of the product would greatly facilitate the convincing of his or her neighbors.

During the first year of the program, compost would be delivered to the farm of the selected individual at no cost to him. The farmer would conduct the test in as scientific a manner as the local situation would permit under the supervision and guidance of a local agricultural adviser. The test was designed to demonstrate the usefulness of compost in three aspects that were particularly important to the farmers. These aspects were: (1) meeting the NPK requirements of the crop, (2) increasing the water-holding capacity of the soil, and (3) increasing yield. A plot in which compost was the only source of NPK ("control" plot) was not included in the tests because no farmer would be willing or could afford to risk obtaining a lower than normal yield by relying upon an untested procedure.

At the same time that the leader farmer is engaged in his test, an agricultural or other appropriate agency should conduct a project designed to demonstrate the utility of compost in a more exhaustive and scientific manner than is possible by an individual farmer.

12.4.2.2. Case 2

Another excellent method is demonstrated by the 2-year demonstration project conducted by the U.S. Bureau of Solid Waste Management (now, the U.S. EPA) at Johnson City, Tennessee (Wiles, 1975). The demonstration program had two principal objectives: (1) to investigate under field conditions the potential uses of compost and the effect of each use on crop production and (2) to introduce the product to potential users and observe their reaction to the prospect of continuing to use the compost after the completion of the demonstration program. Volunteer farmers were given sufficient compost to meet the rates specified for their respective tests. An indication of the level of participation is the fact that the tests involving the effects of compost on tobacco yield involved 25 farms.

Application rates investigated depended upon the crop involved in the particular test. Thus, the range of loadings was 27–143 tons/ha. Crops investigated in the demonstration program included: tobacco, corn, tomatoes, and ornamental plants. Although the responses from all of the farmers in terms of yields were favorable, the most favorable came from those who raised high-value cash crops.

An approach similar to that in Case 2 could be used for the landscaping, nursery, or other potential markets. In short, the use of demonstration plots is an effective means of educating and "selling" potential users. Training for the sale force should also be conducted periodically.

12.4.3. Selling the Product

In some countries, the amounts of compost produced each year have increased substantially. This increase has been primarily due to changes in waste management policies and environmental regulations (such as the Landfill Directive in the EU). These changes have, in many cases, forced the producers to market compost as a replacement for other well-established products. However, to expand the markets for compost, it is important to not necessarily replace existing products but to expand the usage and to develop new uses.

Marketing specialists always emphasize the importance of analyzing the needs and the potential of each sector. The analysis should include delivery requirements, storage capabilities, and pricing policies. The seller must clearly understand the needs and requirements of the targeted market, and to be able to speak knowledgeably on how compost can best meet those particular needs. Advantages accompanying the use of compost must be clearly demonstrated.

12.4.3.1. Example 1

The first example is the strategy followed by an entrepreneur in the U.S. to promote the compost that he produces. The approach was strictly aimed at the production and sale of compost. The venture began on a very small scale, but since its beginning it has expanded to the extent that 4500 tons of compost are being produced and marketed per year. It is operated as a wholesale/retail business (Anonymous, 1982). The entrepreneur stated that 90% of his company's marketing deals with making potential users aware of the existence of his company. The promotional efforts include lectures before garden clubs and presentations at a nearby radio station. The company has also purchased time at radio station and space at a local newspaper. Additional helpful steps included the acquisition of a suitable brand name and logo, and the development of a rapport with the local governmental representatives. The company's composting site is surrounded by an attractive 3.2-ha garden that gathers favorable publicity for the product. In promotional efforts, care is taken to emphasize that composting is a recycling and energy-conserving activity and, as such, transforms local liabilities into an asset.

12.4.3.2. Example 2

The second example is the approach followed by another commercial compost producer. This person sells compost as a part of an integrated agronomy advisory service in California (Anonymous, 1982). In 1981, approximately 91,000 tons of compost were distributed by the producer's company. Since the compost is used on agricultural soils that range from sandy, alkaline soils to moist, acidic humus, the company follows a strongly regionalized, site-specific approach in marketing. To promote awareness of the product in the farming community, the company employs a sales force, makes use of magazine and radio advertising, and submits articles for publication in state farm publications. According to the president of the company, the most effective form of advertising is the word-of-mouth publicity generated by satisfied customers.

12.4.4. Basic Requirements for Achieving a Sustainable Market

The development of a sustainable market for composting requires more than education and selling. There are other factors that also come into play. Among the factors are: consistency of quality and sustained availability of the product, proper distribution, and a sound pricing policy.

For effective and economical use by potential users as well as for wide acceptance, organic fertilizers should have the following five characteristics: (1) the concentration of NPK should be sufficiently high in order to keep the cost of transporting the material needed to meet NPK requirement at a reasonable level (the overall amount of compost required is reduced as its NPK increases); (2) the moisture content should be such that handling is facilitated and accordingly, the cost of transport is reduced; (3) the compost should not contain any toxic materials and pathogens; (4) unpleasant odors should not be noticeable; and (5) the particle size should be relatively uniform and sufficiently small so as to enhance its aesthetics and to promote ease of application.

Because of the variations among various types of composts with respect to visual and nutritive characteristics, grading is recommended so as to ensure the most effective and satisfactory utilization of the product. A particular composting facility may decide to produce only one type of compost, or it may decide to segregate the finished compost into fractions on the basis of quality. Effective use is ensured by matching type of application with the quality of compost suited for the application. Consequently, a relatively low grade of compost would be adequate for the reclamation of excavations and denuded forests. On the other hand, a high grade of compost is required for row crop production.

As it was indicated in previous sections, efforts to establish formal systems of grading are relatively recent developments. Although guidelines have been proposed by federal and state agencies, no formal set of regulations have been issued in the United States. Recent developments include inputs by federal and state agencies and by market forces. Some European countries have developed guidelines and minimum requirements.

Characteristics that enter into proposed grading schemes include NPK content, particle size and uniformity, amount of contaminants (e.g., glass, plastics), freedom from pathogens and toxic and hazardous substances (insecticides, pesticides), and degree of maturity.

According to one classification scheme (Cal Recovery Systems, 1988), a *Grade-1* compost product would: (1) contain no pathogens and toxic substances; (2) have a uniformly small particle size of less than 1.2–2 in. (3–5 cm); (3) be sufficiently mature to be stable and not inhibit growth of root hair; (4) have a NPK content of at least 3%; and (5) have a C/N not greater than 25/1. In addition to a Grade-1 classification, a further classification into Grades 2 and 3 is suggested. *Grade-2* compost would: (1) have a maximum particle size, for example, 1.2–2.4 in. (3–6 cm) larger than that of Grade-1 compost; (2) include some glass and bits of plastic; (3) be free of pathogens; (4) have a C/N of about 40/1; and (5) be relatively mature. The *Grade-3* classification would be relegated to compost products that did not meet the specifications for Grades 1 and 2.

Regulations in force in a few states in the U.S. are directed to the finished product. Most of the regulations limit the use of the material on the basis of concentrations of heavy metals, toxic organic compounds (particularly PCBs, insecticides, and herbicides), and pathogens. In general, regulations developed for composting yard waste have been less stringent than those for composting MSW or biosolids.

It is important to emphasize an overriding factor — namely, consistency of the product. Efficient crop production depends upon the use of a soil amendment of known composition and physical characteristics. Variation in consistency detracts from the utility of the product and as a consequence leads to a loss of consumer interest. Therefore, it is extremely important that the compost meet a fixed set of specifications.

Another important consideration for compost market development is the establishment of quality assurance programs and programs that are designed to develop specifications for the various types of composts (Harrison et al., 2003; Hollingworth, 2004; Buklis, 2005).

12.4.5. Marketing Plan

One of the most important elements in marketing any type of material is the preparation of a marketing plan. One of the key elements in a marketing plan deals with product positioning. Product positioning must consider: market segments, geographic location, and product or application. Market research helps in decision-making processes with how to position the product and assists in determining other important factors such as: characteristics, sales price, transport, competition, infrastructure, and technical expertise required (Alexander, 2004).

12.5. The Real Economic Dimension of the Compost Market in Key EU Countries

The real economic dimension of the compost market depends not only upon the quantity of end products that could be sold in potential markets, but also upon the selling prices of compost. Most of the official studies of the EU present in their analysis a figure named "Compost marketing hierarchy indicating market prices and volumes" (Carlsbæk, 2000) in which the different market segments with the indication of their relative size in €/m^3 [from small (S) up to extra large (XL)] are shown in decreasing order of price range. In Table 12.5, the prices reported, according to the classification of that study, are the following: minimum, maximum, and average. The last column in the table represents the extent of each market segment. The data show that the extra large (XL) segment of

Table 12.5. Classification of market outlets for compost by level of prices and market extent in the European Union

Users	Label	Price			Market size
		Minimum (€/m^3)	Maximum (€/m^3)	Average (€/m^3)	
Greenhouses	GH	20	40	30.0	Medium
Sports turf	ST	15	40	27.5	Small
Nurseries	N	10	30	20.0	Small
Landscaping	LS	10	20	15.0	Large
Topsoil mix	TS	10	15	12.5	Medium
Private gardens	PG	5	20	12.5	Large
Horticulture	OH	2	6	4.0	Medium
Reclamation	R	0	4	2.0	Small
Wine and fruit	WF	1	6	3.5	Medium
Agriculture	A	0	3	1.5	Extra large
Miscellaneous, general	M			12.9	

Source: Carlsbæk, 2000.

market belongs to agriculture, which, at the same time, is able to pay only the lowest prices for compost. Large portions of the physical market defined as large (L) would be, on the contrary, pertinent to private gardens (PGs) and landscaping (LS) segments. The capability to pay (per cubic meter of compost) seems to be middle/high. Finally, medium (M) or small (S) market portions would appear to be other segments distributed among users independent of their capability to pay (poor or rich markets). Rich market segments would have a medium (M) or small size (S) and would correspond to the following: greenhouses, sports turf, and nurseries. We must remember that not every small or medium market is necessarily a rich market.

The aim of this section is to evaluate the real economic importance of these market segments since any successful marketing policy should be performed taking into consideration the entity and composition of buyers' spending capability. Therefore, it has been necessary to reconstruct the size of the composting market of key EU countries in terms of tons sold (Wrap, 2002) to each market segment (tons transformed then in cubic meters on the basis of 450 kg per ton plus 10%) deducting the quantities from various countries' data and reclassifying them among segments. In addition, user classification, on the basis of market size (% of the total market of all countries examined), has been conducted as follows: S — small $<5\%$; M — medium ≥ 5 to <10; L — large ≥ 10 to <30; XL — extra large ≥ 30; NC — not classified.

From Table 12.6, it is possible to argue that the experimental classification of our study conducted in key European countries corresponds to only 5 out of 10 market segments cited by Carlsbæk in Table 12.5. In general, Carlsbæk tends to overestimate the entity of some segments, defined as medium, while in our study they appear to be small, such as greenhouses, topsoil mix, reclamation, and wine and fruit. On the other hand, he underestimates the private gardens segment, defined as medium (M) rather than large (L). In terms of quantity, both studies recognize the importance of the agricultural segment as extra large (XL) and that of landscape as large (L).

Countries contribute to the compost market in very different measures: more than half of the European market (about 54%) of these eight countries is supplied/formed (from the demand point of view) by Germany. Germany is the largest producer of compost and processor of biowaste due to its considerable animal stock and due to its imports of MSW from European partner countries for environmental purposes. Very far, in second place, are: The Netherlands (11% of compost market), France (10%), in third place, not too far behind, Italy and the United Kingdom (both at 6%), and in the last places are Denmark (5%), Austria (4%), and Belgium-Flanders (3%). Note, however, that the major fraction of quality compost originates from source-separated biowaste and is processed in large plants in The Netherlands and in Sweden.

The picture does not change when countries are arranged according to market share distribution among segments as it emerges from the data not in physical terms but in value; the results of our research are given in Table 12.7. Actually, Germany, with 49% of the total value, remains the principal supplier/user of compost marketed in the eight countries considered, but it loses weight in terms of percentage of value with respect to percentage of quantity. The explanation of this performance could be found in the lower unit value (price) of its end products, probably due to the lower quality of its feedstock.

Table 12.6. Entity of market outlets for compost in key EU countries by segment (1999–2001)

Users/countries	AT	BE (FI)	DK	F	D	IT	NL	UK	Total	%	Calculated market extent
Classes of use (000 m^3)											
Greenhouses	0	23	0	0	0	0	176	0	199	1	Small
Sports turf	0	0	0	0	0	0	0	0	0	0	NC
Nurseries	0	0	68	0	616	0	0	0	684	4	Small
Landscaping	198	125	111	144	1672	145	176	0	2571	16	Large
Topsoil mix	0	75	0	144	0	0	0	458	677	4	Small
Private gardens	132	94	367	239	440	0	176	0	1448	9	Medium
Horticulture	66	60	0	80	1760	581	308	0	2855	17	Large
Reclamation	33	61	120	160	880	36	0	143	1432	9	Medium
Wine and fruit	0	0	0	144	0	0	0	0	144	1	Small
Agriculture	198	27	102	0	3168	399	924	367	5185	32	Extra large
Miscellaneous	33	21	85	686	264	48	0	51	1188	7	M
Total	660	486	854	1595	8800	1210	1760	1018	16,383	100	

Source: Elaboration from Wrap, 2002; data by Chang and Iseppi (co-authors of this chapter).

Table 12.7. Value of market outlets for compost in key EU countries by segments (1999–2001)

Users/countries	AT	BE (FI)	DK	F	D	IT	NL	UK	Total	%	Calculated market extent
Value of market by segment (000 €)											
Greenhouses	0	685.5	0	0	0	0	5280	0	5965.5	5	S
Sports turf	0	0	0	0	0	0	0	0	0	0	
Nurseries	0	0	1366	0	12,320	0	0	0	13,686	11	L
Landscaping	2970	1874	1665	2153	25,080	2178	2640	0	38,560	31	XXL
Topsoil mix	0	942	0	1794	0	0	0	5727	8463.1	7	M
Private gardens	1650	1173	4588	2991	5500	0	2200	0	18,102	15	L
Horticulture	264	241.2	0	319	7040	2323	1232	0	11,419	9	M
Reclamation	66	121.6	239	319	1760	72.6	0	285	2863.2	2	S
Wine and fruit	0	0	0	502.4	0	0	0	0	502.43	0	S
Agriculture	297	40.84	154	0	4752	599	1386	550	7778.2	6	M
Miscellaneous	424	268.6	1097	8813	3392	622	0	654	15,271	12	L
Total	5671	5347	9108	16,892	59,844	5795	12,738	7216	122,611	100	

Source: Prepared by Chang and Iseppi.

Mutatis mutandis, France reaches 14% of the total value of compost marketed in the countries examined (as opposed to 10% in terms of quantity), presumably due to the higher quality of feedstock and end product. Regarding the six other countries, the market shares remain nearly the same, starting from value data with respect to those based on quantity. This means that qualitative standards of compost in these countries have a certain degree of uniformity.

The relative importance of market segments in terms of value is very different from those in terms of quantity, with the exception of greenhouses, whose share (5%) remains small (S). It shows that all other segments, which can demand higher unit prices, also gain in their share and change in category of market size toward a more important one, e.g., nurseries move from S to L (11%), landscape from L to XL (31%), topsoil mix from S to M (7%), private gardens from M to L (15%), horticulture from M to L (9%), and miscellaneous from M to L (12%). This takes place while segments with low unit prices undergo a reduction of market share in terms of value with respect to quantity, e.g., reclamation from M to S (2%), and wine and fruit from S to VS (very small). In summary, it is evident, from an economic point of view, that a reversal in the weight of market share for compost (in terms of value with respect to quantity) in favor of landscape and its associated activities (gardens, parks, greenhouses, nurseries, and top soil mix) has taken place and will reach 71% and as opposed to agriculture (comprehensive of wine, fruits, and horticulture), which will drop to 15%.

The hypothesis that could be formulated concerning the theoretical framework of the compost market is that, in general, J.B. Say's law is applicable. J.B. Say's law states that "supply creates its own demand." Germany's case is enlightening: where a plentiful and stable supply exists, demand is automatically created. Due to the relatively high transport costs, processors tend to establish their production units near major sources of constant feedstocks. It is in the neighborhood of processing plants that potential demand for compost becomes real since customers can minimize transport costs. As a suggestion for future research, one could focus attention on production costs in order to determine the relative convenience of composting with respect to alternative treatment methods.

12.6. Quality Certification and Labeling for Compost in the European Union

At the time of this writing (2004), the European Union does not have a common standard quality certification for compost. However, some member countries have adopted specific standards and many other are in the process of doing so. An EU initiative, to improve the present situation for biodegradable waste management and to help meet the targets of the Landfill Directive 1999/31/EC, proposes some specifications for composting and compost (European Commission, 1999). The European Commission has made a commitment that, by the end of 2004, a directive on biowaste, including catering waste, will be prepared with the aim of establishing rules on safe use, recovery, recycling, and disposal of this waste and of controlling potential contamination [fourth recital in Regulation (EC) No 1774/2002].

The commitment reads: "*By the end of 2004 a directive on compost and other biowaste will be prepared with the aim to control potential contamination and to encourage the use of certified compost*."

In the first place, this commitment aims to satisfy the need to establish quality standards for composting in order to ensure safe, long-term, beneficial application, to prevent damage to the soil resource, and to preserve soil properties and its multi-functionality, with particular reference to croplands. In the second place, the commitment emphasizes the importance to boost the recovery of organic matter in order to fulfill the various goals indicated by the Communication on the Soil Strategy (European Commission, 2002) itself (fight against erosion and desertification, use of soils as a "sink" of carbon, enhancement of biological fertility and biodiversity, etc.). *Working document: biological treatment of biodegradable waste 2nd draft*, as prepared by DG Environment (European Commission, 2001), was comprehensively discussed among member states and stakeholders. "Although this document is subject to being more or less modified, it may well serve as a directory of key issues to be considered when defining a consistent strategy for the sustainable management of biodegradable resources" (ASSURE, 2004, p. 1). Moreover the Commission announced in the Communication *Toward a Thematic Strategy on Soil Protection* [COM (2002) 179] that it will present proposals for the revision of the Sewage Sludge Directive 86/278/EEC and for a Directive on the biological treatment of biodegradable waste (European Commission, 2003).

12.6.1. Process Validation Test for Composting

Typically, an indicator organism is used to determine the effectiveness of the treatment in sanitizing biodegradable waste. This test shall be carried out for each treatment plant within 12 months of startup. The indicator organism shall be *Salmonella senftenberg* W775 (H_2S negative). These roles apply only to biological treatment plants producing more than 500 tons of treated green and wood waste per year or 250 tons of treated biowaste per year (European Commission, 2001).

12.6.2. Management of the Composting Process

The composting process shall be carried out in such a way that a thermophilic temperature range, a high level of biological activity under favorable conditions with regard to moisture content and nutrients, and an optimum structure and optimum air distribution are guaranteed over a period of several weeks. During the course of the composting process, the entire mass of biowaste shall be mixed and exposed to an appropriate temperature as in the following scheme.

This applies only to biological treatment plants producing more than 100 tons of treated green and wood waste per year or 50 tons of treated biowaste per year.

The relevant parameters of biological treatment (temperature, moisture, turning frequency for composting and temperature, as well as hydraulic detention time for anaerobic digestion) shall be recorded each day during the sanitation phase referred to in the section

Table 12.8. Suggested temperatures and treatment times as a function of method of composting

Method of composting	Temperature (°C)	Treatment time (weeks)	Turnings
Windrow composting	≥55	2	5
Windrow composting	≥65	1	2
In-vessel composting	≥60	1	N/A

Source: European Commission, 2001.

on process management. These records shall be kept for 5 years and made available to the competent authorities upon request.

In order to allow a proper monitoring and the process validation procedure, the biological treatment plants shall have appropriate openings in order to allow the insertion and extraction of samples and the recording of relevant parameters of the process (European Commission, 2001, p. 17).

A listing of the proposed temperatures and treatment times as a function of method of composting is presented in Table 12.8.

12.6.3. Requirements for the End Product

Absence of *Salmonella* sp. in 50 g of compost/digestate (under review) and absence of *Clostridium perfrigens* in 1 g of compost/digestate (under review).

The compost/digestate shall have less than three germinating weed seeds per liter. In the context of community, standards should be developed for the process validation test, the end product requirements, and for sampling. Until these standards are approved, member states may apply national standards and procedures.

The compost should be produced, imported, traded, and marketed in the European Community according to one of the environmental quality classes presented in Table 12.9 for each relevant parameter considered individually. Compost, through its samples, must comply with relevant parameters as follows: if in any 12-month period, 2, 4, or 12 series of samples are taken, the maximum permitted number of samples that fail to conform to any given parameter will be 1, 1, or 3, respectively. The deviation allowed from the statutory limit of samples, which fail to conform to any given parameter, will be 20% (for each issue). The limits apply to the compost just after the composting phase and prior to any mixing with other materials.

12.6.4. Quality Certification and Assurance in EU Countries

The European Union has established rules for environmental certification of quality. The Eco-Management and Audit Scheme (EMAS) is a voluntary scheme for organizations willing to commit themselves to evaluating and improving their environmental performance.

Table 12.9. Environmental quality classes for compost and stabilized

Parameters	Compost/digestate*	
	Class 1	Class 2
Cd (mg/kg dm)	0.7	1.5
Cr (mg/kg dm)	100	150
Cu (mg/kg dm)	100	150
Hg (mg/kg dm)	0.5	1
Ni (mg/kg dm)	50	75
Pb (mg/kg dm)	100	150
Zn (mg/kg dm)	200	400
PCBs (mg/kg dm)**	–	–
PAHs (mg/kg dm)**	–	–
Impurities >2 mm	<0.5%	<0.5%
Gravel and stones >5 mm	<5%	<5%

*Normalized to an organic matter content of 30%.
**Threshold values for these organic pollutants to be set consistent with the Sewage Sludge Directive.
Source: European Commission, 2001, p. 18.

This scheme was launched in April 1995 and revised in 2001. EMAS is open to any organization in the public and private sectors committed to improving its environmental performance. It is open to Member States of the European Union and to the European Economic Area (Norway, Iceland, and Liechtenstein). An increasing number of new member countries are also implementing the scheme. The European Commission has recognized that the International Standard for Environmental Management Systems, ISO 14001, can provide a stepping stone for EMAS. The adoption of ISO 14001, as the environmental management system element of EMAS, will allow organizations to progress from ISO 14001 to EMAS without duplicating their efforts.

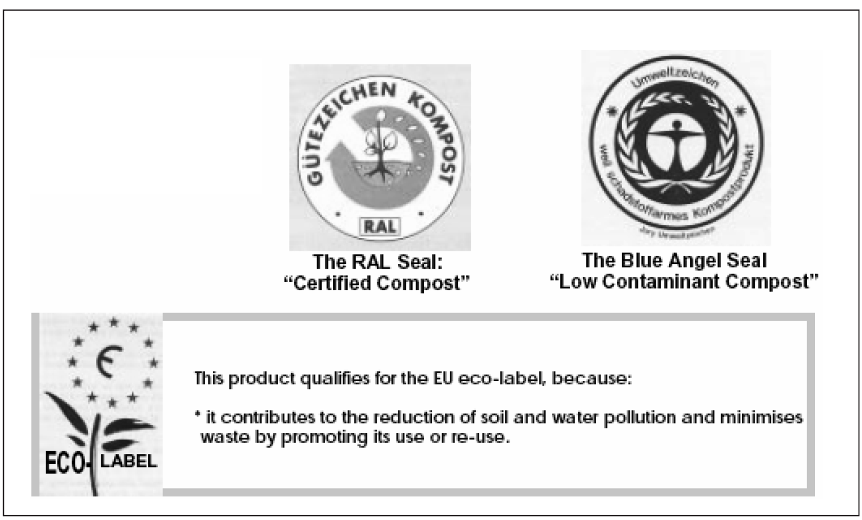
Over recent years, marketing analyses show that all users of compost demand a standardized quality product that is monitored by independent organizations. Many investigations in Europe indicate that quality and marketing of the end product is the most crucial issue in composting. Both producers and users are of the opinion that a sustainable recycling of organic wastes demands clear regulations regarding what is suitable to be recycled and how it should be managed and controlled. A well-founded quality assurance program would definitely increase sustainable recycling of organic wastes. The introduction of separate collection and composting of organic residues must, therefore, go hand in hand with the introduction of a quality assurance system. Assuring compost quality is more than just fulfilling a number of limit values for heavy metals. Compost quality plays a central role and influences all stages of the treatment of organic residues (Barth, 2003). The production of compost of a defined, consistent, high quality can be assured by implementing a variety of measures. In addition to the collection of carefully sorted waste and appropriate treatment techniques, regular quality checks are also required as a basis for the product declaration and correct application.

As far as the specific field of composting is concerned, only Germany has made substantial progress toward establishing a quality assurance program. The Federal Compost Quality Organization (Germany) is the carrier of the compost quality label (RAL). Germany has had two types of quality seals that can be obtained for composts: the Bundesgütegemeinschaft Quality Seal and the Blue Angel seal (RAL, 1998). Both of them are authorized under the German Institute for Quality Certification and Declaration (RAL), an agency that has a scope similar to UL in North America (Fig. 12.1).

The central role of quality assurance is also seen in the countries with developed composting systems like Austria, Denmark, The Netherlands, and Belgium. These countries (including Germany) have established an extensive quality management system for the composting plants, in which around 400 composting plants participate at the moment. Several other countries such as Sweden, Norway, Italy, and France are in the conceptual design phase.

Quality assurance links the end product with all the various elements of the organic treatment and its cycle forms the first step toward a comprehensive quality management of the composting plants.

A survey of compost quality efforts in various countries classifies them in the following four categories according to the status of quality assurance/certification of compost: (1) fully established quality assurance system (Austria, Belgium-Flanders, Germany, The Netherlands); (2) just started with quality assurance system for compost or proposal for quality criteria (Denmark, France, Spain-Catalonia, Sweden, UK, Norway); (3) successful source separation system (Italy); and (4) no official efforts until now (all other countries, excluding new members).



Source: Brinton, 2000, p. 14

Fig. 12.1. Selected quality seals for compost products.

12.6.5. *Types of Control Systems*

Most of the European countries adopted statutory quality standards that contain a continuous monitoring or a voluntary quality assurance. However, it is important to note that 70% of the source of separated organic waste in the EU is composting or digestate from 520 large plants that are located in The Netherlands and Sweden.

Germany's RAL-quality label system assesses the quality of the end product. An application can be filed for the quality sign by every compost producer and supplier through the regional organization (Ministry of the Environment, Germany, 1992). In The Netherlands and in Belgium, the control of the end product is associated with a production control. Almost the same procedure is followed in Belgium with a continuous production monitoring.

In The Netherlands, the certification of the quality sign describes a very large internal quality monitoring of the compost production with weekly tests of parameters from each compost charge. Similar trends can be observed in Austria, where the quality sign demands a product/process diary that requires almost 100 parameters (Barth, 2003).

12.6.6. *Heavy Metal Contents*

The quality criteria for compost with respect to concentrations of heavy metals vary in the European countries concerning the amount, the requirements, and the limits. Statutory limits are diversified by class and by country. A review of the limits set on heavy metals and the allowed deviation in the EU countries with respect to community standards is shown in Table 12.9. It is possible to demonstrate that most of them (e.g., Austria, Belgium-Flanders, Denmark, Germany, Ireland, Luxemburg, Sweden, United Kingdom) are within the proper range with respect to Cd, Cr, Hg, and Ni; except Spain for Cd, France for Cd, Hg, Ni, and Pb, and Italy for Hg. Some other heavy metals are near the upper boundaries, e.g., Pb in Ireland, Luxemburg, Spain, United Kingdom, and France. With respect to Zn, four countries are very near to the upper threshold: Germany, Luxemburg, Spain, and the United Kingdom. Moreover, only Denmark, Italy, and the United Kingdom set limits enormously out of range for Cu (1000, 300, and 200 mg/kg dm rather than 150 mg/kg dm, respectively). Similarly, Austria, Italy, and Denmark established a very high limit for Zn (500 mg/kg dm by Austria and Italy; and 4000 mg/kg dm by Denmark). Consequently, countries' adjustments to the new EU standards that will be set forth by the forthcoming Biowaste Directive would be very difficult, especially for Zn and Pb and less for Cu and mutatis mutandis for the following countries: France, Italy, United Kingdom, Denmark, and Spain.

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Index