COMPOSTING AS A WAY TO CONVERT CELLULOSIC BIOMASS AND ORGANIC WASTE INTO HIGH-VALUE SOIL AMENDMENTS: A REVIEW

Martin A. Hubbe,*,a Mousa Nazhad,b and Carmen Sánchez c

Plant-derived cellulosic materials play a critical role when organic wastes are composted to produce a beneficial amendment for topsoil. This review article considers publications dealing with the science of composting, emphasizing ways in which the cellulosic and lignin components of the composted material influence both the process and the product. Cellulose has been described as a main source of energy to drive the biological transformations and the consequent temperature rise and chemical changes that are associated with composting. Lignin can be viewed as a main starting material for the formation of humus, the recalcitrant organic matter that provides the water-holding, ion exchange, and bulking capabilities that can contribute greatly to soil health and productivity. Lignocellulosic materials also contribute to air permeability, bulking, and water retention during the composting process. Critical variables for successful composting include the ratio of carbon to nitrogen, the nature of the cellulosic component, particle size, bed size and format, moisture, pH, aeration, temperature, and time. Composting can help to address solid waste problems and provides a sustainable way to enhance soil fertility.

*Contact information: a: Department of Forest Biomaterials; North Carolina State University; Campus Box 8005; Raleigh, NC 27695-8005; b: Asian Institute of Technology, P.O. Box 4, Klong Luang, Pathumthani 12120, Thailand; c: Laboratory of Biotechnology; Universidad Autonoma de Tlaxcala, Apartado postal 129, Tlaxcala, Tlax. CP. 90000, Mexico; * Corresponding author: hubbe@ncsu.edu*

INTRODUCTION

Composting can be defined as the controlled aerobic conversion of mixed organic materials into a form that is suitable for addition to soil. The goal of this article is to review the literature to better understand the roles of wood, crop residues, and other plant-derived (lignocellulosic) materials in composting processes. Almost every published description of composting emphasizes the use of one or more lignocellulosic materials in the recipe to achieve a successful outcome.

Primary goals of composting have included the safe handling of organic wastes and enhancement of soil's fertility. Thus, composting has been the subject of articles of key historical importance, as well as review articles and books (Howard 1935; Gray and Biddlestone 1971; Gray et al. 1971, 1973; Gouleke 1972; Minnich et al. 1979; Dickson *et al.* 1991; Beck 1997; Dougherty 1998; Tuomela *et al.* 2000; Moss *et al.* 2002; Ebeling 2003). The authors of these works list a wide range of additional anticipated benefits of

composting. These include the cost-effective, sustainable procurement of a substitute for synthetic fertilizers (Beck 1997; Moss *et al.* 2002), establishment of a bacterial environment that supports healthy root systems (Beck 1997; Tiquia *et al.* 2002; Danon *et al.* 2008); and conversion of objectionable organic wastes into a stable, benign substance having less volume (Dickson *et al.* 1991; Dougherty 1998). Dougherty (1998) also lists reduction of odors, especially in the case of feces composting, improving the bulking and water-holding abilities of soils, speeding up the biodegradation process compared to what would happen in nature, destroying weed seeds, pathogens, and insect eggs, incorporation of nitrogen, phosphorus, and potassium into more suitable chemical compounds, and inhibition of molds and fungi in soils. Compost also can provide a steady supply of nutrients to growing plants and increase the soil's ability to retain essential minerals (Stevenson 1985). When composting processes are not carried out under optimized conditions, then there is a risk that pathogens originating from plant and food residues can remain in the compost, which raises concern that pathogens may be carried into agricultural products and the human food supply (Hultman 2009). Zucconi *et al.* (1981, 1985) also raised concern about toxic effects from the use of improperly treated waste matter.

Resource and Waste Management

Strong motivation for the development of composting systems has arisen as municipalities struggle to find safe and economical ways to handle their organic wastes. In addition to reducing the volume of material, composting can markedly decrease the presence of infection-causing microbes (Atkinson *et al.* 1996; Moss *et al.* 2002; Tiquia *et al.* 2002; Maboeta and van Rensburg 2003; Rao *et al.* 2007; Cayuela *et al.* 2009). In addition, various toxic effects of manure and other materials towards plant organisms are strongly reduced (Sesay *et al.* 1997; Rantala *et al.* 1999, 2000; Volchatova *et al.* 2000; Jouraiphy *et al.* 2005; Hanajima *et al.* 2007; Alburguerque *et al.* 2009). Reduction of odors also provides strong incentive for composting, though the process needs to be optimized with care to ensure adequate aeration, sufficient cellulosic material, and other factors to minimize release of odors during biodegradation (Tchoganoglous *et al.* 1993; Atkinson *et al.* 1996; Dougherty 1998; Veeken *et al.* 2004; Xi *et al.* 2005; Bonneau *et al.* 2008). Greenhouse gas emission, including methane, also can be minimized by inclusion of sufficient cellulosic material (Bonneau *et al.* 2008) or phosphogypsum (Hao *et al.* 2005) during composting.

Paper mill sludge usage

Given the lignocellulosic origin, it makes sense to consider composting as a waste handling strategy for sludge from the pulp and paper industry. A number of studies have reported promising results (Brouillette *et al.* 1996; Atkinson *et al.* 1997; Sesay *et al.* 1997; Poggi-Varaldo *et al.* 1999; Rantala *et al.* 1999, 2000; Larsen and McCartney 2000; Baziramakenga *et al.* 2001; Charest and Beauchamp 2002; Das *et al.* 2002; Das and Tollner 2003; Lalande *et al.* 2003; Levy and Taylor 2003; Marche *et al.* 2003; Charest *et al.* 2004; Gea *et al.* 2005; Beauchamp *et al.* 2006; Roberts *et al.* 2007; Monte *et al.* 2009). Sludge that is high in cellulosic content can be paired with nitrogen-rich wastes such as pig manure (Lalande *et al.* 2003). Despite the known recalcitrance of lignin (see

later), essentially all reports have indicated suitable reduction in mass, resulting in a non-hazardous product having beneficial effects when added to soils.

Wastepaper usage

Effects of various types of wastepaper have been evaluated in composting experiments (Shin and Jeong 1996; Raymond *et al.* 1997; Brown *et al.* 1998; Eklind and Kirchmann 2000; Vikman *et al.* 2002; Venelampi *et al.* 2003; Zorpas *et al.* 2003; Rao *et al.* 2007; Saludes *et al.* 2008; Sung and Ritter 2008). There has been some concern that water-resistant treatments or coatings of certain paperboard products could impede composting. Raymond *et al.* (1997) found that wax-treated corrugated cardboard could be successfully composted, as long as the nitrogen content was adjusted to a suitable range. Sridach and coworkers showed that barrier-coated boards of various types, including polyethylene-coated board, could be successfully biodegraded under suitable soil conditions, albeit at a somewhat slower rate in comparison to uncoated board (Sridach *et al.* 2006, 2007; Nazhad *et al.* 2006). Venelampi *et al.* (2003) noted that there was less carbon dioxide produced from lignin-rich mechanical pulps, in comparison to kraft pulps, which are low in lignin content; these results are consistent with lignin's higher resistance to biodegradation. Brown *et al.* (1998) noted that phosphorus addition can be beneficial during the composting of wastepaper, which usually lacks that element.

Lopez Alvarez *et al.* (2009) found that too high a proportion of wastepaper in compost can have an inhibitory effect on decomposition. The adverse effects were not observed if the amount of paper in the compost was kept below 27%.

Other waste materials

In addition to the cellulosic components that are the main focus of this article, composting has been viewed as a current or potential solution to the disposal of a wide range of waste materials. These include kitchen and market wastes, agrictulural wastes, including manure, and industrial wastes, including wastes from the food industry. Some waste categories, such as yard wastes and crop residues, are high in cellulosic matter. In urban areas some of these wastes may be collected separately, a circumstance that facilitates later combining different components in favorable ratios. Later sections of this article will consider (a) the range of different kinds of cellulose-containing matter that can be incorporated into composting processes, and (b) considerations involved in the mixing of such materials with other waste materials.

Soil Improvement

Suitably prepared compost can provide multiple benefits to soils. For example, Camberato *et al.* (2006) observed that composted sludge from paper mill waste increased the organic content of the soil, improved its physical properties, provided nutrients, and raised the pH to a more ideal range. The treated soil also had a higher water-holding capacity and ability to hold onto essential metals (higher ion exchange capacity). It has been found that lignocellulosic materials added to compost can act as bulking agents, allowing greater access to air (Chang and Chen 2010).

Humus is a widely used term for the brown organic matter that is characteristic of rich topsoils (Howard 1935; Golueke 1972; Crawford 1983; Varadachari and Ghosh

1984; Dickson 1991; Beck 1997; Tuomela *et al.* 2000; Venelampi *et al.* 2003). In an approximate sense, humus can be described as a collection of particularly recalcitrant breakdown products of lignin from various decomposed biomass sources. Notably, the lignin component within biomass tends to be decreased less than the cellulose or hemicellulose components of biomass during composting (Tuomela *et al.* 2000; Eiland *et al.* 2001a,b; Jouraiphy *et al.* 2005; Huang *et al.* 2006; Alburquerque *et al.* 2009; Spaccini *et al.* 2009). It is notable, however, that certain bacterial isolates have shown enhanced capability for lignin breakdown (Vargas-Garcia *et al.* 2007b). Though compost is considered to be a good source for nutrients, research has shown that the nitrogen and phosphorus components tend not to be as long-lasting in the amended soil, compared to lignin-derived matter (Baziramakenga *et al.* 2001).

Nitrogen fixation issues

Nitrogen fixation and incorporation of nitrates into soil has been cited as an outcome of compost use (Huang *et al.* 2001b; Beauchamp *et al.* 2006; Choi *et al.* 2007; Cayuela *et al.* 2009). Beauchamp *et al.* (2006) isolated nitrogen-fixing bacteria from compost and showed they were able to convert N_2 to nitrate only when there was sufficient cellulosic material to act as an energy source to drive the biochemical process. Earlier work by the same team showed that nitrogen fixation was increased by forced aeration (Brouillette et al. 1996) when composting paper mill deinked sludge. Work by Atkinson *et al.* (1996) indicated that though there was considerable cycling of nitrogen within the bacterial populations present during composting, it was hard to discern clear evidence of fixation. A key issue of concern is that nitrogen can be lost from the process as NH_3 gas during composting (Eiland *et al.* 2001a,b; Choi *et al.* 2007). Bueno *et al.* (2008) found that conditions to avoid such loss can include use of a long composting time, low particle size, medium moisture content (40%), and medium to low aeration level. Addition of base to compost usually is minimized or avoided, since high pH converts NH_4^+ to the more volatile NH_3 (Dickson *et al.* 1991; Recovery Systems 2005; Saludes 2008). In any case, McGinn and Sommer (2007) found that the composting of manure resulted in much less release of ammonia gas in comparison to land-application of the same manure.

A BRIEF ANALYSIS OF THE COMPOSTING PROCESS

Detailed descriptions of the composting process have been included in various publications, of which the following are representative (de Carvalho *et al.* 1991; Tchobanoglous *et al.* 1993; Genevini *et al.* 1997; Eklind and Kirchmann 2000; Pichler *et al.* 2000; Maboeta and van Rensburg 2003; Garcia-Gomez *et al.* 2005; Jouraiphy *et al.* 2005; Huang *et al.* 2006; Lhadi *et al.* 2006; Said-Pullicino *et al.* 2007; Spaccini and Piccolo 2008; Vernoux *et al.* 2009). Although there are a great many variations in composting practices, certain steps appear to be broadly shared. In general, the process starts with the gathering together of biomass components, the optional reduction of size of some of the materials, mixing (or optional layering) of the components, and formation into a pile. Some other essential ingredients are water, sufficient air, and a sufficiently

large mass so that self-insulation, as well as the decay process, results in a strong increase in temperature. Increases in temperature have been shown to be correlated with rates of CO_2 production (Atkinson *et al.* 1997), which can be taken as concrete evidence of the oxidation processes inherent in composting.

Dougherty (1998) divides the main kinds of compost piles into four categories: open static piles, turned windrows and piles, aerated static piles, and in-vessel systems. Figure 1 gives a schematic illustration of predominant air movements in a static pile. The decay processes within the pile provide heat, which causes convection of heated air upwards, and fresh air is drawn in from the sides of the pile to renew the oxygen supply. As shown, some air may also enter the pile due to wind and diffusion. The other three types of composting systems mentioned above can be viewed as different ways to overcome certain characteristic drawbacks of static pile composting, including uneven temperatures in the pile, channeling of air, and the possibility of anaerobic zones. Windrows are elongated piles, a shape that can conveniently be built and turned by tractors. Aerated windrows can be prepared by placing the pile over perforated pipes installed at ground level. In-vessel composting is sometimes used in urban settings; in some designs the decaying material is pushed through a long chamber in a quasi-continuous manner.
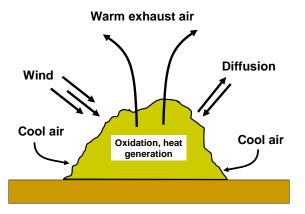

Figure 1. Convection currents and other factors affecting aeration of a static compost pile

Phases of Composting

The composting process, especially when it is carried out in batch mode, can be divided into different phases characterized by temperature. Figure 2 represents typical temperature changes that can be expected for a static pile and for an aerated pile. The phases are conventionally defined in terms of the kinds of bacterial and fungal populations that thrive in different temperature ranges, *i.e.* psychrophilic (optimum at 13 °C), mesophilic (21-48 °C), and thermophilic (45-68 °C) (see Dickson *et al.* 1991). Ambient temperatures are expected to prevail in a freshly-mixed compost recipe, but bacteria will very soon start to work on easily oxidizable materials in the mixture, and the metabolism will cause the temperature to rise. The mesophilic bacteria are known to be effective for breakdown of biomaterials (Dickson *et al.* 1991), whereas the thermophilic conditions are important in terms of detoxifying the system, breaking down seeds, *etc.*

Ball (1997) refers to similar temperature ranges, but identifies phases of composting according to dominant chemical transformations that are expected to take place: oxidation (13 $^{\circ}$C), reduction (18 to 24 $^{\circ}$C), degradation (29 to 63 $^{\circ}$C), conversion (13 to 63 $^{\circ}$C), and maturation (insignificant internal heating). As shown in Fig. 2, it is typical for the temperature to gradually rise, to peak within the thermophilic range, and then gradually fall as the compost enters the maturation phase. As illustrated by the solid line in the figure, it is also possible to control the temperature, especially in aerated systems and when thermocouples are placed in the pile.
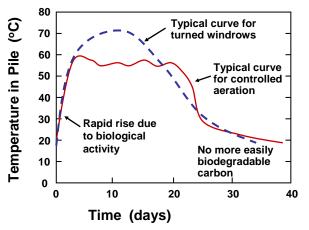

Figure 2. Typical temperature curves for static composting and aerated composting

As noted by Golueke (1972), a typical compost pile starts to heat up shortly after the ingredients have been combined and gathered together, and the temperature usually increases from ambient to 50 $^{\circ}$C within one to two days. After four days the temperature can reach 60 to 70 $^{\circ}$C, and temperatures as high as 75 $^{\circ}$C have been achieved. Though high temperatures can pervade most of the pile, the outermost several centimeters will be substantially cooler.

Bacterial and fungal succession

A remarkable aspect of composting is the more or less complete replacement of one set of microbes with another set, and then another, as the process works its way through the different temperature zones. Table 1 lists organisms that have been identified in a variety of composted mixtures. Adney *et al.* (2008) provide an overview of the most important bacteria and fungal types, including pictures and descriptions.

Several groups of researchers have studied microbial population changes during composting of various materials (Atkinson *et al.* 1997; Tiquia *et al.* 2002; Charest *et al.* 2004; Sole-Mauri *et al.* 2007; Tang *et al.* 2007; Wang *et al.* 2007a; Yu *et al.* 2007; Danon *et al.* 2008; Petric and Selimbasic 2008; Cayuela *et al.* 2009). Neklyudov *et al.* (2008) reviewed the related literature and found a correlation between the quality of compost and the microorganisms involved in composting. Figure 3 lists, by class, various micro-organisms that can be present during a typical composting operation.
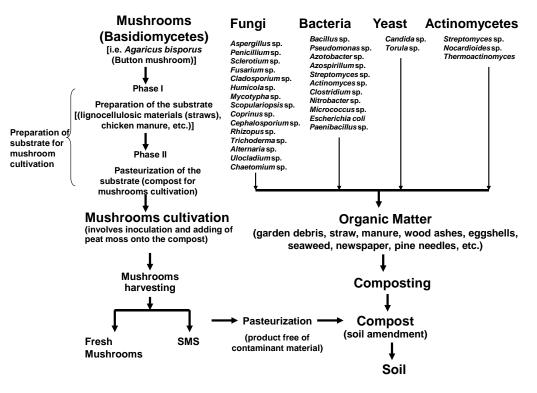
Figure 3. Biological organisms participating in composting processes

Table 1. Types of Microorganisms Involved with Stages of Composting

Composting Stage	Involved Organism in the Composting Stage	Type of Microorganism	Reference
Mesophilic (composting before mixing the pile)	*Bacillus* sp. *Paenibacillus* sp. Actinomycetes *Aspergillus fumigatus*	Bacteria Bacteria Filamentous bac. Fungi	Silva et al. 2009a
At the end of the composting procedure (samples in different points)	*Aspergillus fumigatus* *Emericella* sp. *Aspergillus ochraceus* *Aspergillus terreus* *Penicillium oxalicum*	Fungi Fungi Fungi Fungi Fungi	Dias et al. 2009
Thermophilic (at the beginning of the composting process, immediately after the heat peak) At the cooling and maturation of the composting procedure	*Rhabditidae* sp. *Panagrolaimidae* sp. *Diplogasteridae* sp. *Cephalobidae* sp. *Mononchoides* sp. *Ditylenchus filimus*	Nematode Nematode Nematode Nematode Nematode Nematode	Steel et al. 2010

Table 1 (continued)**.** Types of Microorganisms Involved with Stages of Composting

Composting Stage	Involved Organism in the Composting Stage	Type of Microorganism	Reference
At the cooling of the composting procedure	_Escherichia coli_	Bacteria	Hassen et al. 2001
Mesophilic and thermophilic	_Streptococcus_ sp.	Bacteria	
At the remainder of the composting cycle	_Bacillus_ sp.	Bacteria	
Mesophilic	_Feacal coliforms_ _Pseudomonas_ sp. _Streptococcus_ sp. _Proteus_ sp. _Serratia_ sp. _Bacillus_ sp.	Bacteria Bacteria Bacteria Bacteria Bacteria Bacteria	Taiwo and Oso 2004
Thermophilic	_Aspergillus_ sp. ** _Fusarium_ sp. ** _Penicillium_ sp. ** _Humicola_ sp. * _Mycotypha_ sp. * ** _Scopulariopsis_ sp. * _Cephalosporium_ sp. * _Trichothecium_ sp. **	Fungi Fungi Fungi Fungi Fungi Fungi Fungi Fungi	
Cooling down stage	_Aspergillus_ sp. ** _Fusarium_ sp. * ** _Penicillium_ sp. ** _Cladosporium_ sp. ** _Mycotypha_ sp. * ** _Scopulariopsis_ sp. * _Coprinus_ sp. * ** _Cephalosporium_ sp. * ** _Trichothecium_ sp. *	Fungi Fungi Fungi Fungi Fungi Fungi Fungi Fungi Fungi	
Mesophilic	_Pseudomonas_ sp. _Azotobacter_ sp. _Azospirillum_ sp. _Bacillus_ sp.	Bacteria Bacteria Bacteria Bacteria	Rebollido et al. 2008
Mesophilic and thermophilic	_Chaetomium thermophile_ _Malbranchea sulfurea_ _Thermomyces lanuginosus_ _Torula thermophila_	Fungi Fungi Fungi Yeast	Salar and Aneja 2007
At the cooling and maturation	_Thermoactinomyces_ sp.		Chang et al. 2009; Tuomela et al. 2000.

* Found in composting in pot
** Found in composting in pile

As indicated in Fig. 3, the growing of mushrooms has much in common with the non-specific composting practices discussed so far in this paper. For instance, the decay of lignocellulosic matter can be considered as a main source of energy for the process. However, soil amendment can also been obtained from mushrooms. The mushrooms (i.e. *Agaricus bisporus*) cultivation generates an enormous amount of used "spent" substrate, which might also be a source of environmental contamination. Several uses for spent mushrooms substrate (SMS) have been evaluated, and some of them have already been established. Some studies have been done on the use of SMS in vegetable and flower greenhouses, in field vegetable and fruit crops, in nursery and landscape gardening, and in soil amendment (Sánchez 2004). The SMS is the post-harvest mushroom substrate.

The compost that is used for culturing the most cultivated mushroom worldwide, *A. bisporus* (button mushrooms), is prepared by a two-stage process. In the first stage, a mixture of raw materials such as straw, hay, corn cobs, cotton seed hulls, animal manure (such as stable bedding or poultry manure), and gypsum are assembled, wetted, and then formed into a long pile. Water addition is controlled, and the pile is dissembled and reformed at intervals. In the second stage, pasteurization is done to prepare the compost for a selective growth medium on which *A. bisporus* will be inoculated (Sánchez 2004). The inoculation is carried out using "spawn," which is the mycelium (in this case of *A. bisporus*) developed on cereal grain, e.g., wheat, rye, or millet. The purpose of the mycelium-coated grain is to rapidly colonize the specific bulk growing substrate. The success of mushroom production depends in great part on the quality of the spawn (Sánchez 2004, 2010). Finally, a layer of sphagnum peat moss mixed with ground limestone is top dressed onto the compost, and mushrooms grow on the peat. When the harvest is finished, farmers steam-pasteurize the entire contents of material in the growing room and dispose of the peat moss and compost that remain. This product is sold as spent mushroom soil (SMS) or spent mushroom compost (SMC) (see www.mushroomcompost.org). Mushroom soil is great for gardens as a slow release organic fertilizer (2-1-1, pH 6.8) when mixed into soil.

Bacteria are unicellular organisms without nuclei, and it has been estimated that a gram of soil often contains about 10 million bacterial cells (Gans *et al*. 2005; Hultman 2009). Many of these types of viable cells in the past would have been undetected by the available assays, which have relied mainly on culturing of cell colonies in petri dishes. The reason for this is that no single culture medium can be well suited to the very diverse growth conditions required by different organisms in soil (Amann et al. 1995; Whitman *et al*. 1998). New methods, such as polymerase chain reactions and molecular methods, have greatly increased our ability to detect different bacterial types in soil samples. During composting, the bacteria obtain their carbon by the oxidation of the organic waste. While bacteria decompose a variety of organic materials by producing enzymes, they themselves tend to be fragile and incapable or surviving under unfavorable conditions. For instance, changes in temperature, oxygen, moisture, or pH can terminate or inactivate classes of bacteria. Under favorable conditions the life span for one bacterial generation is in the range of 20 to 30 minutes. However, if aerobic bacteria do not receive sufficient oxygen, then the aerobic microorganisms are replaced by anaerobic species, and the latter produce a variety of useless products that are smelly and in some cases toxic to plants.

A key function of bacteria and fungi during composting is to produce cellulolytic enzymes. The varieties and functions of cellulases have been reviewed elsewhere (Haigler and Weimer 1991; Sukumaran *et al.* 2005; Clarke 1997; Taherzadeh and Karimi 2007b; Himmel 2008). Briefly stated, several classes of enzymes have to work together to bring about the effective breakdown of plant material. Cellulose itself requires three types of enzymes for its decomposition: Endo-cellulases (*i.e.* endoglulconases) cut the cellulose macromolecular chain at random positions, decreasing its molecular mass and disrupting its crystallinity. Exocellulases (cellobiohydrolases) start at an exposed end of a cellulose chain and cause the release of successive cellobiose units. Beta-glusocidase (or cellobiase) converts the cellubiose into six-carbon glucose units. The situation is more complicated in the case of hemicelluloses and lignin, due to the greater heterogeneity of bonds within these biomass components (Himmel 2008). In addition, as demonstrated by Kato *et al.* (2004), effective composting requires the action of bacteria that have no cellulolytic activity. Such bacteria can help to regulate the level of oxygen, consume metabolytes that otherwise might inhibit cellulolytic activity, and help to control the pH.

Tchobanoglous *et al.* (1993) described a typical microbial succession in the following terms: First facultative (aerobic) and obligate (anaerobic) bacteria begin to work, and they continue to be active through the mesophilic phase. Then, then after 5 to 10 days, thermophilic fungi become prevalent. Then, during the cooling down, curing, or maturation period, actinomycetes, which are filamentus gram-positive bacteria, as well as molds become prevalent. Decomposition within the compost involves the successive actions of these classes of microorganisms. The term "chemical decomposers" can be applied, since the microorganisms bring about chemical changes to an organic waste. Compost piles also include macro-organisms such as mites, centipedes, sow bugs, snails, multipedes, springtails, spiders, slugs, beetles, ants, flies, nematodes, flatworms, rotifers, and earthworms. The latter can be called physical decomposers, since they mechanically convert the organic waste into small pieces.

Evidence of the action of microbes can be found in the variation of pH during composting. As shown in Fig. 4, the pH generally declines at the start of composting (Tchobanoglous *et al.* 1993).
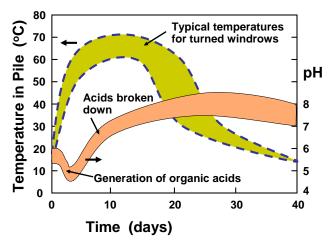

Figure 4. Changes in temperature and pH during a typical static composting operation
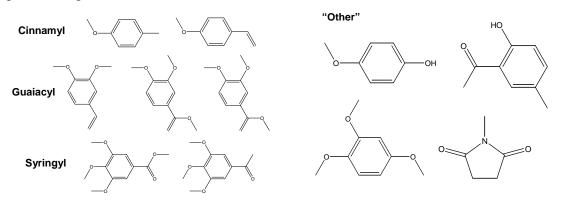
Golueke (1972) has attributed an observed initial decline of pH (as shown in Fig. 4) to the synthesis of organic acids by the bacteria. For instance, hydrolysis of acetate groups on hemicelluloses is an expected source of acetic acid (see Hultman 2009). However, the acids themselves are soon utilized by the microbial community, and the pH rises. The generation of ammonia becomes significant during the rest of the active phase of composting, causing the pH to remain generally in the weakly alkaline range.
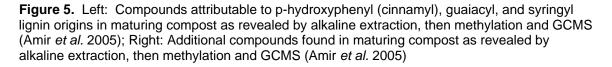
Fungal organisms and succession

As in the case of bacteria, our knowledge of fungal ecology has benefited greatly from advances in experimental methods (VandenKoornhyse et al. 2002). As noted by Anderson and Cairney (2004), fungal communities can be profiled by DNA-sensitive methods, denaturing gradient gel electrophoresis (DGGE), temperature gradient gel electrophoresis (TGGE), single-strand conformation polymorphism (SSCP), terminal restriction fragment length polymorphism (T-RFLP), amplified rDNA restriction analysis (ARDRA), amplified ribosomal intergenic spacer analysis (ARISA), and cloning. Recently a whole additional branch of the family of soil fungi was reported (Porter *et al*. 2008). In addition, because specific fungal species are needed to produce enzymes that can break down specific lignin-related chemical species, it is possible to use changes in the levels of such species as an innovative way to assess the rate of succession of fungal populations (Huang *et al*. 2010).

Organic Matter Content

Another way to characterize the different phases of composting, as well as the relative completeness of a composting process, is by evaluating changes in the organic matter. Various researches have used spectrophometric methods to follow the relative proportions of different humic acid species (Kakezawa *et al.* 1992; Veeken *et al.* 2001; Genevini *et al.* 2002a,b; Marche *et al.* 2003; Lhadi *et al.* 2006). Amir *et al.* (2006) employed methylation of compost components, followed by gas chromatography with mass spectrometry (GCMS); they detected the compounds in Fig. 5 as the most prominent peaks.

Figure 5. Left: Compounds attributable to p-hydroxyphenyl (cinnamyl), guaiacyl, and syringyl lignin origins in maturing compost as revealed by alkaline extraction, then methylation and GCMS (Amir *et al.* 2005); Right: Additional compounds found in maturing compost as revealed by alkaline extraction, then methylation and GCMS (Amir *et al.* 2005)

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As revealed in the left-hand frame of Fig. 5, many of the compounds were clearly related to the main types of phenolic groups found in lignin from different plants. However, as shown in the right-hand frame of Fig. 5, there also were compounds among the humic acids that could not as easily be attributed to breakdown of specific lignin types.

In general terms, the easily degradable components tend to be consumed early in the composting process, and thereafter a succession of reactions can occur, leading eventually to humus, which consists of moieties having relatively great resistance to decomposition. Because each stage of biodegradation requires the successive attack on increasingly recalcitrant matter, the progress of composting also can be monitored by evaluating the activities of different enzymes (Vuorinen 2000).

Nitrogen Fixation and Compost Maturity

Microorganisms require nitrogen for their survival. Although nitrogen in the form of N_2 gas is highly abundant, most microorganisms cannot use it unless it has been converted into either the ammonium form (NH_4^+) or the nitrate form (NO_3^-). Nitrogenase enzymes capable of fixing gaseous N_2 and converting it into the biologically useful forms are produced only by certain nitrogen-fixing bacteria. Figure 6, based on a scheme presented by Douglas (1994), indicates the main chemical processes involved with nitrogen fixation.
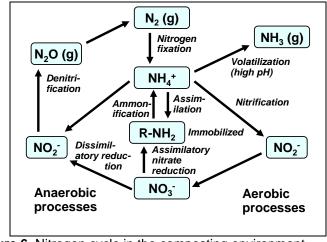

Figure 6. Nitrogen cycle in the composting environment, according to Douglas (1994)

One of the major challenges in composting is how to minimize the loss of gaseous nitrogen (Eiland *et al*. 2001a,b; Choi *et al*. 2007). Nitrogen is primarily stored in the tissues of living and dead organisms. The organic substances eventually break down due to enzymatic processes, resulting in the production of ammonium (NH_4^+). The process is referred to as ammonification or mineralization. Under sufficiently alkaline conditions the ammonium ion is converted into ammonia gas, which can escape to the atmosphere if it is not recaptured. Moist, cooler conditons in the outer layer of a compost pile generally favor the retention of ammonia. Under aerobic conditions much of the ammonium can be converted into nitrite by bacteria from the genus *Nitrosomonas*. Further modification by another type of bacteria, belonging to the genus *Nitrobacter*, converts nitrite into nitrate,

i.e. the nitrification process. Under anaerobic conditions nitrate is converted to ammonia gas or nitrogen gas, both of which escape to the atmosphere.

If the compost has insufficient carbon (low C:N ratio), then the microorganisms use the available carbon and get rid of excess nitrogen by converting it to NH_3 or NH_4^+, depending on the pH. Thus, composts having a relatively high nitrogen content are pH-sensitive. At relatively low values of pH, which are typical of early phases of composting, no release of NH_3 is detected (Beck-Friis *et al.* 2003). If the material to be composted has a relatively high pH, then it can be beneficial to add an acidic material such as aluminum sulfate or sulfuric acid (Ekinci *et al.* 2000). At pH values of 8.5 or higher, the nitrogen is converted to NH_3, often resulting in nitrogen loss from the compost. The release of ammonia to the atmosphere reduces the nitrogen reserve of the compost and may cause odor problems.

As noted by Bernal *et al.* (2009), cellulosic materials in their role as "bulking agents" can help to reduce the loss of nitrogen during composting. The beneficial effects may be attributed not only to better aeration when the compost bed has a bulkier, more porous structure (Chang and Chen 2010), but also due to the fact that addition of the lingnocellulosic material increases the C:N ratio (Ekinci *et al.* 2000). Delgado-Rodriguez *et al.* (2010) found that nitrogen volatilization was minimized when the compost mixture had medium-to-high aeration, medium-to-high C:N ratio (60 to 70), and high moisture content (>55%). Elwell *et al.* (2002) also found benefits of aeration to reduce nitrogen loss when composting mixtures of hog waste and sawdust. Dinel *et al.* (2004) found that there was less nitrogen loss to air if paper mill sludge compost was controlled by mechanized turning according to a schedule, and by keeping the pH and moisture content in favorable ranges.

Nitrate is a negatively charged ion; thus it is repelled by humus and other negatively charged substances in the compost. As a consequence, nitrate can be found in the leachate from compost. Under anaerobic conditions nitrate is converted into nitrogen gas and nitrous oxide by heterotrophic bacteria (denitrification), which eventually diffuses into the atmosphere. Most of the nitrogen found in soil has come from the atmostphere through rain, lightning, or bacteria, and it is likewise recycled back to the atmosphere.

Researchers often use the C:N elemental ratio to evaluate the degree of completion of a composting process (Tchobanoglous *et al.* 1993; Dougherty 1998; Charest *et al.* 2002; Suzuki *et al.* 2004; Jouraiphy *et al.* 2005; Mangkoedihardjo 2006; Brito *et al.* 2008). In general, one expects the carbon content to decline as CO_2 is released, whereas the retention of organic nitrogen in compost is usually regarded as highly desirable. An increased level of nitrates relative to ammonium nitrogen also can be used as evidence of successful nitrogen fixation in compost (Suzuki *et al.* 2004; Brito *et al.* 2008). Pichler *et al.* (2000) found evidence that much of the nitrogen content of compost was tied up in peptide structures, some of which were quite resistant to degradation. Bueno *et al.* (2008) defined "acceptable chemical properties" as a Kjeldahl nitrogen content of at least 3.2%.

Various measurements have been used to judge the degree of completeness, or "maturity," of composts. Larre-Larrouya and Thuries (2006) found that the methoxyl group content of the humic acid-like fraction of compost provided better evidence of

maturity, compared to measurements of ash, organic carbon, nitrogen, or lignin. Mangkoedihardjo (2006) used the ratio of biological oxygen demand (BOD) to chemical oxygen demand (COD) as a means of reassessing what value of C:N should be used to judge maturity of compost; a ratio less than 14 was recommended on this basis. Fukushima *et al*. (2009) defined a "humification index," which is the ratio of humic carbon to non-humic carbon, and proposed that the index be used as a measure of compost maturity. The index was determined by acidification of compost extract to precipitate the humic acids. Dougherty (1998) lists the following additional attributes that can be expected in fully mature compost: a high cation exchange capacity, a high water absorption capacity, no tendency to heat up spontaneously even when the compost is turned, a brown color, and an earthy smell. Golueke (1972) noted that municipal waste loses its pungent odor within six or seven days of windrow composting and acquires an earthy odor. Golueke (1972) and Tchobanoglous *et al*. (1993) included a final drop in temperature, mass reduction, a rise in redox potential, oxygen uptake, the growth of *Chaetomium gracilis* fungus, and starch-iodine test results as additional evidence of compost maturity. An increased content of humic acid-like matter, relative to the total amount of carbon, can be a further way to define compost maturity (Spaccini and Piccolo 2008; Lima *et al*. 2009). Said-Pullicino *et al*. (2007) found that the ratio of hydrophobic to hydrobilic carbon should rise above unity before compost can be considered mature, relative to the germination of seedlings. Though Khalil *et al*. (2008) suggested the use of redox potential measurements as a way to assess the progress of composting, it is clear from their data that significant changes in the redox potential of compost were generally limited to the more active phases of composting, and there was little further change in redox potential as maturation took place.

GOVERNING PARAMETERS AND OPTIMIZATION

Considerable study has been devoted to determining optimum conditions of composting, and good overviews of such work and related instructional material have been published (Dickson *et al*. 1991; Tchobanoglous *et al*. 1993; Beck 1997; Dougherty 1998; Ebeling 2003).

The Initial C:N Ratio

The ratio of carbon to nitrogen is the parameter most often considered in studies dealing with the composition of composted mixtures (Dickson *et al*. 1991; Atkinson *et al*. 1996; Shin and Joeng 1996; Ball 1997; Beck 1997; Raymond *et al*. 1997; Brown 1998; Dougherty 1998; Martin-Olmedo and Rees 1999; Ekinci *et al*. 2000; Larsen and McCartney 2000; Eiland *et al*. 2001a,b; Huang *et al*. 2001a, 2004; Charest and Beauchamp 2002; Saletes *et al*. 2004; Lhadi *et al*. 2006; Zhang and He 2006; Wang *et al*. 2007a; Brito *et al*. 2008; Ruggieri *et al*. 2008; Vernoux *et al*. 2009). As noted by Beck (1997), if the C:N ratio is too high, temperature in the compost pile may fail to rise, whereas if C:N is too low, the mixture may emit unpleasant odors. It has been recommended that compost mixtures should be prepared so that the initial C:N values are between about 25:1 and 40:1 (Dickson *et al*. 1991) or even as high as 50:1

(Tchobanoglous *et al.* 1993). Given the wide range of density, particle size, and lignin content of different lignocellulosic materials, one can easily understand that the upper end of this range may be difficult to define in general. Many instructional books about composting contain tables of typical C:N values for different biomass materials (*e.g.* Ebeling 2003). As mentioned earlier, the C:N ratio is expected to fall during composting, and its final value can be used as one criterion of the relative maturity of the product.

The C:P Ratio

Compared to the C:N ratio, the ratio of carbon to phosphorus has received much less research attention. However, the relative amount of phosphorus can be a limiting factor when the mixture contains a high proportion of paper (Brown *et al.* 1998), which is poor in that element. Brown *et al.* (1998) found that the initial C:P ratio should be between 120:1 and 240:1 when the C:N ratio is 30:1.

Cellulose Source

Lignocellulose from the following sources has been considered in various composting studies: paper (Ekinci et al. 2000; Baziramakenga *et al.* 2001; Rao *et al.* 2007; Sung and Ritter 2008); cardboard (Itevaara et al. 1997; Raymond *et al.* 1997; Eklind and Kirchmann 2000; Francou et al. 2008; Saludes *et al.* 2008); pulp mill solids (Levy and Taylor 2003); sawdust (Atkinson *et al.* 1996; Huang *et al.* 2001b; Hwang *et al.* 2002; Marche *et al.* 2003; Tiquia *et al.* 1997; Zhang and He 2006; Silva *et al.* 2009b); straw (Biddlestone et al. 1986; Eklind and Kirchmann 2000; Eiland *et al.* 2001a,b; Veeken *et al.* 2001; Chapman and McCartney 2005; Amir *et al.* 2006; Tang *et al.* 2007; Wang *et al.* 2007a; Petric and Selimbasic 2008; Silva *et al.* 2009b); rice husk and hulls (Genevini *et al.* 1997; Anda *et al.* 2008); sugar cane residue (Boopathy *et al.* 2001); *alperujo* olive oil wastes (Garcia-Gomez *et al.* 2005; Alburquerque *et al.* 2009); cotton wastes (Garcia-Gomez *et al.* 2005); brewery waste (Garcia-Gomez *et al.* 2005); leaves (Eklind and Kirchmann 2000; Huang *et al.* 2001a,b, 2004); peat (Eklind and Kirchmann 2000;); cocoa husks (Rao *et al.* 2007); oil palm residuals (Saletes *et al.* 2004); woodshavings (Eklind and Kirchmann 2000); and woodchips (Maboeta and van Rensburg 2003; Suzuki *et al.* 2004; Silva *et al.* 2009b). Because most of the materials were evaluated separately in the cited studies, and because the types of biomass differ in multiple respects, useful generalizations might be limited to the following: All classes of lignocellulose can be used successful in composting, and testing can help in determining the relative biodegradability of each material, as well as any recommended preparations.

Particle Size

By reducing the sizes of lignocellulosic components in compost, one can increase the area that is readily accessible to enzymatic action (Nazhad et al. 1995). Thus, particle size reduction can be a practical first step in composting. Various authors have recommended particle size reduction in general as a means of accelerating the process (Golueke 1972; Beck 1997; Bending and Turner 1999; Lhadi *et al.* 2006; Nazhad *et al.* 2006; Bueno *et al.* 2008). Tchobanoglous *et al.* (1993) recommended particles between about 2.5 and 7.2 cm in size. Bueno *et al.* (2008) obtained best results when the cellulosic materials were chopped to about 1 cm. Fujino *et al.* (2008) found that they

could further reduce resistance to biodegradation if they ground the material with a mortar and pestle. Lhadi *et al.* (2006) observed when the particle size is small enough, then it can be easier to discern effects on biodegradability attributable to chemical differences. Dickson *et al.* (1991) recommended varying the size of particles in a compost mixture in order to achieve a good air-permeability of the mixture. Bending and Turner (1999) also observed that particle size may influence nitrogen mineralization or protection of aging microbial tissues from attack by microorganisms. Sharma *et al.* (1998) reported higher intentional biogas emission (over 70%) by an anaerobic digester using smaller size particles.

Bed Size

The optimum compost bed size depends on whether the pile is aerated, whether it is turned, and whether its extremities are partly contained in insulating materials. In the case of a static pile Dickson *et al.* (1991) recommend a minimum volume of approximately one cubic meter to ensure sufficient self-insulation, so that the material will heat up.

Bed Structure

Though compost can be contained in a variety of specialized structures, the costs *vs.* benefits of such structures need to be scrutinized. Beck (1997) asks the rhetorical question, "Why spend a whole lot just to help something rot?" In many cases an uncontained pile or windrow will suffice, as long as one pays attention to other factors (Tchobanoglous *et al.* 1993). Golueke (1972) noted that some entrepreneurs have been eager to make money selling non-essential items to inexperienced composters, and such items can include most kinds of compost bins.

Aerated systems can be constructed rather simply, using perforated pipes or channels at ground level, over which compostable material is placed in a pile or windrow (Dougherty 1998). Completely contained systems employing continuous, plug-flow throughput of the compost mixture (Tchobanoglous *et al.* 1993; Dougherty 1998; Hwang *et al.* 2002) can be justified when space is severely limited or in settings where odors must be stringently avoided. For household composting, Ebeling (2003) has recommended alternating green and brown layers, which can be considered as a rudimentary form of mixing.

Aqueous Conditions

Through one might anticipate that the aqueous chemical conditions within a compost pile might play a large role in determining the rate and outcome of the process, related issues have received surprisingly little attention. For instance, ammonium sulfate can be added to get the process started more quickly (Dickson *et al.* 1991). Presumably the ammonium serves as a bioavailable source of nitrogen to support bacterial growth.

Compost pH

Initial pH values in the range 4.2 to 7.2 (Dickson *et al.* 1991) or 7 to 7.5 (Tchobanoglous *et al.* 1993) have been recommended. It has been reported that the production of lactic and acetic acids during initial degradation of biomass often leads to

an acidic pH in the range of 4.2 to 5.5 (Hultman 2009). In cases where the material to be composted is very acidic, it sometimes is recommended to add a small amount of lime or fly-ash (Dickson *et al.* 1991; Beck 1997).

Later, in the thermophilic stage of composting, the pH can rise to 9, resulting in release of ammonia, and thereafter the pH usually returns back to near-neutral conditions as the compost becomes mature (Hultman 2009). With an increase in the pH to about 6 the organic acids are decomposed by microorganisms, and the associated rise in pH is sometimes taken as evidence of successful composting. Optimum pHs for bacterial and fungal activities have been reported in the ranges of 6 to 7.5 and 5.5 to 8.9, respectively (Golueke 1972).

Caution is required whenever alkali is added to compost. Excessively alkaline conditions can promote the release of ammonia gas (Saludes *et al.* 2008), as indicated in Eq. (1).

$$NH_4^+(aq) \ + \ OH^-(aq) \rightarrow NH_3(g) + H_2O \qquad\qquad (1)$$

Figure 7 indicates that ammonia gas can be formed in the pH range of 8.5 to 9. To counter such an effect, Ekinci *et al.* (2000) found that such release could be minimized by the addition of aluminum sulfate, an acidic material. Kim *et al.* (2004) found that a pH of 7.5 was ideal for production of a compost-derived cellulase. Likewise, Zambrano *et al.* 2010 advocated the use of well controlled amounts of green liquor dregs, a $CaCO_3$-rich byproduct of kraft pulping, to minimize the pH drop often observed at the onset of composting.
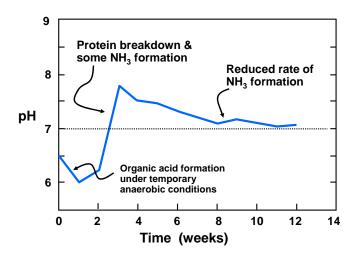

Figure 7. Variation of pH with time during a typical composting operation (after Gray and Biddlestone 1971)

Salinity

Excessively high salinity has been mentioned as a potential problem during the composting of pig manure (Huang *et al.* 2004). When the compost is added to soil, high salt levels can have an adverse effect on some plants.

Surfactants

Shi *et al.* (2006) observed that a non-ionic surfactant and a biosurfactant had stimulatory effects on the microbial populations in compost. Though more study would be needed to fully explain such phenomena, the findings are consistent with facilitation of enzyme transport to substrate surfaces.

Moisture Content

Moisture is important in composting processes for two reasons: 1) it facilitates substrate decomposition through mobilizing microorganism activities; and 2) it provides better conditions for nitrogen fixation in compost. A low moisture condition can restrict the mobility of microorganisms. Under drier conditions the ammonium and ammonia present generate a higher vapor pressure; thus conditions are more favorable for nitrogen loss. Ammonia is highly soluble in water; thus higher moisture content inhibits ammonia escape from compost and promotes nitrogen fixation. Addition of water is sometimes recommended for preventing premature drying (Atkinson *et al*. 1996). The ammonia that is preserved in a moist environment can subsequently become immobilized in the biomass of new generations of microorganisms (Liang *et al*. 2000).

The moisture level in a compost mixture should be optimized in order to achieve the best results (Beck 1997; Bueno *et al.* 2008). Dickson *et al.* (1991) and Dougherty (1998) recommend a moisture content in the range 40 to 60%, whereas Tchobanoglous *et al.* (1993) recommend 50 to 60% moisture. Petric *et al*. (2009) recommend an initial 69% moisture for composting poulty manure and wheat straw. Bueno *et al.* (2008) found most favorable results at the intermediate moisture level in their experimental design, which was 40%. Hwang *et al.* (2002) recommend a moisture content of 46% for the composting of kitchen garbage. It has been recommended to maintain a 60% moisture content in the outer layer of compost (Recycled Organics Unit 2007). The lower temperature in the outer layer of a compost pile can be favorable for conversion of ammonia to more stable forms, *i.e.* nitrogen fixation (Rynk *et al.* 1992). However, excessively wet compost fills the smaller pores, limiting the oxygen transport, and causing emission of odors that are associated with anaerobic conditions. Accordingly, Zhang *et al*. (2009) recommended that the moisture condition be kept below 65%.

Inoculation

Addition of suitable bacteria or fungi may benefit the composting process, and some inoculant products have been available for sale (Dickson *et al.* 1991). Various authors have shown that highly effective cellulose-decomposing microorganisms and the enzymes produced by such organisms can be effective composting agents (El-Din *et al.* 2000; Hart *et al.* 2003; Xi *et al.* 2005; Vargas-Garcia *et al.* 2007a). Xi *et al.* (2005) observed higher rates of oxygen uptake and reduced production of odorous gases in inoculated compost mixtures. Nazhad *et al.* (2006) and Sridach *et al.* (2007) observed that inoculum accelerated degradation of barrier-coated boards in soil environments. Kim *et al.* (2004) isolated a cellulase-secreting bacterium from cattle manure and then used it effectively in composting. Rashad *et al*. (2010) reported enhancement of decomposition of recalcitrant substances in rice straw compose that had been inoculated.

Rovshandeh *et al.* (2007) observed more effective composting of hardwood bark in systems that had been treated with white rot fungus.

Addition of starting culture, incorporating microorganisms and pH adjustment, has been recommended either for the deactivation of inhibitiing agents, or acceleration of composting process, or both. In a typical composting operation short-chain organic acids are decomposed, so there is often no need for any pH modifier. However, organic acids, mainly lactic and acetic acids, are produced during storage as well as the first phase of composting (specifically in food organic waste), dragging the pH down to 4 to 5, which is harmful for microorganism growth. In addition, for most composters it is desirable to have compost ready in a final form sooner rather than later.

Not all investigators have reported positive effects of inoculation. Kostov *et al.* (1991) observed only marginal increases in the rates of composting sawdust and bark when cellulose-decomposing microorganisms were intentionally added. Maboeta and van Rensburg (2003) observed no benefit of inoculant addition when composting sewage sludge and woodchips. One of the logical reasons why addition of bacteria or fungi to compost mixtures sometimes fail to significantly benefit the process is that most organic wastes already contain diverse communities of organisms, each of which can multiply rapidly when favorable conditions are established (Golueke 1972). This explains, for example, why Boopathy *et al.* (2001) were able to use an alternative strategy in which molasses was used to stimulate native bacterial and fungal populations, enabling the composting process to start more quickly.

Aeration

Aeration provides necessary oxygen to decomposers, removes water vapor and other gaseous products, and can be used to adjust temperature to a desired level. Though the contact of oxygen-rich air with biomass is essential for composting to occur, the challenge lies in accomplishing such contact within a relatively compact mass of material, such that temperatures are able to rise, further stimulating the metabolic processes. Spreading the compostable material in a thin layer simply won't work. Rather, convection of air, due to the heating within the pile, has a major effect, as was illustrated in Fig. 1. Also, some aeration undoubtedly occurs due to wind and due to diffusion of air. However, most references recommend further measures to promote air contact during composting, either turning of the compost pile or use of forced aeration.

Tchobanogouls *et al.* (1993) stated that aerobic composting requires that the oxygen within the pile be kept at a concentration at least half that of ambient air. Wang *et al.* (2007b) made detailed measurements of turned and aerated piles and found oxygen concentrations below 1.5% in the air within non-aerated compost piles. The oxygen level was always above 4% in aerated piles. By suppressing the amount of air, *i.e.* microaerobic conditions, the thermophilic phase could be extended from 15 days to 23 days. Lopez *et al.* (2002) found that increased aeration favored the action of white-rot fungi in the degradation of lignocellulosic wastes. Zhang *et al.* (2009) found that there was an optimum level of aeration that would minimize emission of odor; however the main adverse consequence of having insufficient air was an observed low rate of biodegradation.

Maeda and Matsuda (1997) and Tamura *et al*. (1999) reported that a higher aeration rate reduced methane and nitrous oxide emissions but increased ammonia volatilization. Beck-Friis *et al* (2003) compared compost aeration at different oxygen concentrations (1%, 2.5%, and 16%). They observed prolongation of the mesophilic phases and reduction of microbial activities at lower oxygen concentration (1% and 2.5%). The ammonia emission was also delayed, and nitrous oxide was not observed in the thermophilic stage. Brouillette *et al*. (1996) reported an increased degree of composting along with increased nitrogen fixation with increased aeration. The differences between the findings can be attributed to differences in composting conditions, the constituent materials, compost structure, and other factors. Contrary results were reported by Roberts *et al*. (2007) who were able to maintain higher quality of compost by loosely covering the pile with a plastic sheet. In particular, the covered piles tended to accumulate more fixed nitrogen during the maturation phase. Likewise, Tumuhairwe *et al*. (2009) observed faster maturation of covered compost piles.

Turning of compost

Various studies have demonstrated beneficial effects of periodic remixing the contents of compost piles, *i.e.* turning (Dougherty 1998; Brito *et al*. 2008; Alburquerque *et al*. 2009; Tirado and Michel 2010). In fact, turning was already advocated by Howard (1935) as part of the Indore composting process, and the practice is recommended in popular books on composting (Ball 1997; Beck 1997). Tchobanoglous *et al*. (1993) write that turning can be used, as needed, to overcome the following problems: charring, drying, caking, and air channeling. Alburquerque *et al*. (2009) found that turning improved results even in the case of aerated compost piles.

The frequency of turning can be an issue, since every turning results in at least a temporary reduction in temperature of the contents. A turning frequency of once or twice a week is recommended by Tchobanoglous *et al*. (1993). Dickson *et al*. (1991) and Beck (1997) recommend turning piles once a week and suggest that more frequent turning may not be a good investment of time and energy. Tiquia *et al*. (1997) found that turning a mixture of swine manure and sawdust every two or four days yielded faster composting, compared to weekly turning; the four-day schedule was judged to be cost-effective. Ball (1997) recommends turning the pile again as soon as the core temperature drops to about 55 °C. Brito *et al*. (2008) observed that turning increased the rate, but did not greatly change the end results of composting of cattle slurry, as long as one is willing to wait long enough for unturned piles to reach completion. The same study showed conclusively that covering of a compost pile with polyethylene adversely affected the process.

Golueke (1972) concluded, on the basis of the small size and temporary nature of temperature drops due to turning, that the biological processes of composting are highly active and somewhat self-regulating. His book recommends turning schedules that depend on moisture content: Piles containing 60 to 70% moisture should be turned at 2-day intervals; whereas piles with 40 to 60% moisture should be turned each 3rd day. One can imagine that a more soggy pile might be in greater need of turning as a means of ensuring adequate aeration.

Forced aeration

A number of studies have considered effects of forced aeration during composting (Brouillette *et al.* 1996; Albuerquerque *et al.* 2009). Brouillette *et al.* (1996) found that forced aeration increased the degree of composting and also increased the fixation of nitrogen. It was found that more rapid composting could be achieved with aeration pipes spaced 2 meters apart, compared with 3 m spacing. Bueno *et al.* (2008) found best composting of legume trimming residues at low to medium levels of aeration. Hanajima *et al.* (2007) found that a sufficiently high level of aeration of anaerobically digested swine manure improved the germination characteristics of the final compost, though there was some loss of nitrogen. Vacuum aeration can be used beneficially in some cases where it is important to collect the resulting gases (Saludes 2008).

Temperature

Temperature is obviously a key variable in composting, since it affects the kinds of organisms that are likely to thrive within a pile. Many authors have focused on changes in temperature during the process (Dickson *et al.* 1991; Atkinson *et al.* 1997; Ball 1997; Dougherty 1998; Tang *et al.* 2007; Vernoux *et al.* 2009). Nelson *et al.* (2003) modeled the thermal behavior of heat generation by biological activity, drawing upon theory from combustion engineering. Conditions for spontaneous ignition and unsteady temperature jumps were considered.

Temperature management

One of the simplest forms of temperature management is that advocated by Ball (1997): observations of falling temperature within a compost pile were used as a signal to judge the opportune time to turn it. Such a practice allows the process to consume any materials that might have been missed due to poor aeration or cool temperatures in some parts of the pile. Likewise, Golueke (1972) offered the following advice if one observes excessively hot temperatures: Make the pile shallower the next time.

Aeration systems offer considerably more flexibility with respect to temperature control. Tchobanoglous *et al.* (1993) noted that aeration systems can be used to control the temperature at a favorable temperature of 55 $^{\circ}$C for an extended period. One relatively simple approach to temperature management is to control the forced air flow between a low and a high setting (Ekinci *et al.* 2000). Although the higher oxygen content in fresh air promotes more rapid metabolism, a sufficiently high rate of air flow will cool the pile. Tchobanoglous *et al.* (1993) recommend holding the system at 50 to 55 $^{\circ}$C initially, then raising the temperature range to 55 to 60 $^{\circ}$C until the temperature falls due to depletion of the cellulosic materials.

Results reported by Tang *et al.* (2007) indicate that there may be an advantage to controlling the temperature in the mesophilic temperature range, favoring populations of proteobacteria and fungi having higher decomposition activity. Vikman *et al.* (2002) found that mechanical pulp fibers were degraded more effectively at lower incubation temperatures of 35 and 50 $^{\circ}$C, whereas bleached kraft paper was degraded effectively also at 58 $^{\circ}$C. Kim *et al.* (2004) found that temperature can be important if one is attempting to optimize conditions for production of certain enzymes or cellulase-secreting bacteria.

Time

Most composters consider time to be a response variable, and in general it can be considered desirable to have compost ready in a final form as soon as practical. Beck (1997) provides a good discussion of the balance between time and money in cases where there is adequate space available. Bueno *et al.* (2008) found that conditions resulting in the best retention of Kjeldahl nitrogen coincided with a relatively long composting time. Suzuki *et al.* (2004) showed that wood chips from clear-cutting could be composted effectively by composting them over a period of 10 months.

Optimization of completeness

Time also can be used as an independent variable with respect to deciding at what point the compost is "ready." The answer appears to depend on how the compost is to be used. For instance Genevini *et al.* (1997) determined that composted cattle slurry was suitable for field application after 56 days. However, 254 days of composting was needed before it was suitable for use in greenhouses with sensitive plants. Smith and Hughes (2001) found that the level of cellulase activity in compost could be used as an indicator of maturity, and that truly mature composes should have a low content of cellulase. Albrecht et al. (2008) suggested that whereas the C:N ratio tends to decrease markedly during the early phases of composting, factors such as the pH, humic acid content, and ratio of humic acids to fulvic acids are more sensitive measures of completeness. Mondini et al. (2006) found in particular that the organic carbon content of alkaline-extract from compost could provide a sensitive measure of humification. Mature composts have a high ratio of humic-like substances.

THE ROLE OF LIGNOCELLULOSICS IN COMPOST

Key roles played by plant-derived, lignocellulosic materials during composting can be classed as structural, absorptive, or having to do with biochemical changes.

Structure

The lignocellulosic material itself, even before it is subject to any biodegradation, can help to reduce the packing density of compost and ensure that the mixture retains sufficient water to enable biological degradation processes to occur (Chang and Chen 2010). Because conventional composting is an aerobic process, the required biodegradation reactions can be facilitated by materials that provide pockets of air or channels for air flow, even when the moisture content is in a suitable range for composting. Various lignocellulosic materials, such as stalks, straw, hulls, leaves, branches, wood chips, sawdust, paperboard scraps, *etc.* can served this role (Genevini *et al.* 1997; Dougherty 1998; Vuorinen 2000; Huang *et al.* 2001a; Saludes *et al.* 2008; Alburquerque *et al.* 2009; Hatten *et al*. 2009; Silva *et al.* 2009a).

The Role of Cellulose

In simplified chemical terms, composting can be viewed as a slow oxidation of biomass, with the production of carbon dioxide (Dickson *et al.* 1991). Cellulose and

hemicellulose are the main carbon sources, accounting for most of the CO_2 and most of the heat. But because the reaction proceeds through biochemical pathways, proteins and enzymes are essential, and that means that there has to be a sufficient amount of nitrogen present in the mixture relative to the amount of carbon. This dependency on biological processes helps to explain why composting guidelines often call for the addition of sufficient cellulosic biomass to achieve a suitable C:N elemental ratio.

The Role of Lignin

The role of lignin has been described in negative terms, as a component that retards the decomposition of lignocellulosic materials (Komilis and Ham 2003). Vikman *et al.* (2002) and Komilis and Ham (2003) found negative correlations between the amounts of lignin in different biomass mixtures and the rates of decomposition. Due to the slow degradation of lignin, the proportion of lignin-derived carbon in the mixture tends to increase during composting (Lima *et al.* 2009). Venelampi *et al.* (2003) observed that delignified paper fibers yielded more carbon dioxide in comparison to mechanical pulp fibers that contain substantial proportions of lignin.

A model of the lignin structure can be a useful starting point when attempting to understand lignin's relative resistance to biological breakdown. Figure 8 shows representational models, based on experimentally determined bond frequencies, to illustrate the kinds of structures within native softwood lignin (Sakakibara 1980; Brunow 1997; Karhunen et al. 1995). Features to be noted include the characteristic phenol-propane structure (mainly guaiacyl in the case of softwood), a diversity of bond types, and a relatively random, three-dimensional nature of lignin. In reality a "single molecule" of lignin would be many orders of magnitude larger than the representations shown in the figure. The progression from the left-hand to the right-hand frame of the figure illustrates how concepts of lignin structure have developed over time (Karhunen et al. 1995).
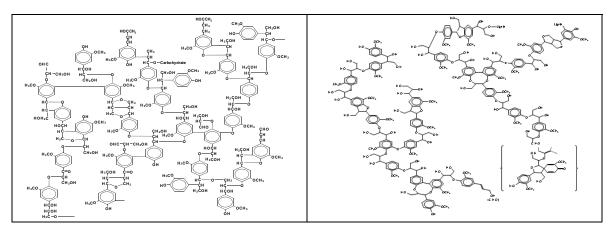

Figure 8. Representative structural models of softwood lignin, illustrating some of the main chemical groups and the variety of covalent bonds participating in the complex, three-dimensional structure; Left: Based on Sakakibara (1980); Right: Based on Brunow (1997).

Lignin as a precursor of humus

Many studies have focused on the chemical structures of lignin-derived materials in compost and in soils (Varadachari and Ghosh 1984; Kakezawa *et al.* 1992; Chen et al.

1996; Volchatova *et al.* 2000; Genevini *et al.* 2002a,b; Garcia-Gomez *et al.* 2005; Amir *et al.* 2006; Huang *et al.* 2006; Lhadi *et al.* 2006; Smidt *et al.* 2008; Spaccini *et al.* 2009). These materials are traditionally classified as either fulvic acids (soluble in water), humic acids (soluble in alkaline water), or humin (insoluble under ordinary aqueous conditions) (Tuomela *et al.* 2000; Garcia-Gomez *et al.* 2005). Anaysis of humic acids has revealed the presence of 4-hydroxybenzoic acid, vanillic acid, 4-hydroxybenzaldehyde, vanillin, syringaldehyde, and acetovanillone (Miikki *et al.* 1994). The dimers dehydrodivanillin and dehydrodiacetovanillone were also found. Though humic acids and fulvic acids have similar chemical structure, differences in the degree of crosslinking and the amount of hydroxyl, carboxyl, and carbonyl groups can account for the observed differences in solubility behavior. Novikova *et al.* (2002) traced increases in the ion-exchange capacity of lignin to the increasing proportions of phenyl, hydroxyl, and carboxyl groups during composting. Smidt *et al.* (2008) confirmed the transformation of lignin to specific humic acids. They also showed that humic acid formation could be enhanced by addition of 2 to 5% of lignin powder to a compost mixture. Amir *et al.* (2006) characterized humic acid structures that could be attributed to the p-hydroxyphenyl propane, guaiacyl, and syringyl units of the lignin derived from different lignocellulosic sources. Montoneri (2005) showed that lignin-derived matter in compost can be sulfonated, facilitating its subsequent analysis by NMR.

Laccases, manganese peroxidases (MnP), and lignin-peroxidases (LiP) belong to the enzymatic complexes that degrade lignin and are classified as phenoloxidases. In general terms, the presence of lignin renders cellulosic materials more resistant to biodegradation. Lignin can be described as a three-dimensional, semi-random polymer composed of substituted phenolpropane units that are linked together by a variety of bond types (Sjöström 1993). The most frequent and most easily cleaved bonds within lignin are the β-O-4 (beta-aryl ether) bonds, whereas other linkages such as β-β, β-5, and 5-5 are more resistant to chemical degradation (Sjöström 1993; Brunow 2001). Enzymes required for complete degradation of lignin tend to be produced after most of the other nutrients in the pile have been consumed. Kirk and Farell (1987) attributed the activation of lignin degrading fungi to changes in the level of nitrogen. Wood contains a limited amount of nitrogen, so the production of lignin-degrading enzymes is delayed until enzymes capable or breaking down more readily attacked molecular species have done their work.

The C:N ratios of some materials that are commonly used in compost mixtures are shown in Fig. 9 (Storl 1979). The shading in the figure is meant to emphasize the point that most composted materials require mixing with other ingredients in order to achieve a suitable balance between carbon and nitrogen, as needed for effective composting.

Different fungal species play different roles in the degradation of biomass. Basidiomycetes fungi have been reported to be the most effective degraders of lignocellulose material (Sánchez 2009). In particular, white rot fungi are the most effective degraders of lignin (Kirk and Farell 1987; Hatakka 2001; Hammel 1997). Brown rot fungi (basidiomycetes family), which mainly degrade the polysaccharide components of wood, can nevertheless accelerate the degradation of lignin by creating channels in the biomass through hydroxylation and demethylation reactions. Hatakka

(2001) characterizes lignin degradation processes by white rot fungi as being mainly oxidative, degrading aromatic groups, decreasing aliphatic, phenolic, and methoxyl content of lignin, and generating new carbonyl groups.

	C:N	
Sawdust	500:1	"Too high in C
Paper	200:1	if used alone"
Straw	40-80:1	
Corn stalks	60:1	
Used mulch	60:1	
Dry leaves	60:1	
Old hay	30:1	
Wilted greens	20:1	"Ideal range,
Vegetable scraps	20:1	by itself"
Grass clippings	15:1	
Legume hay	15:1	
Manure	15:1	
Kitchen scraps	10:1	"Too high in N
Blood meal	5:1	if used alone"

Figure 9. C:N ratio of some common compost materials (Storl et al. 1979)

Relative to soil fertility, the slow-to-degrade lignocellulosic breakdown products in composts and soils can be expected to have various helpful functions. The high content of carboxylic acids, in concert with the phenolic groups, is believed to be responsible for the ion exchange capacity of humic acids, and this provides a mechanism by which many essential metal ions can be held within the soil until they are needed by plants. Figure 10 shows a structure that have been proposed to account of the strong ion exchange capacities of these moieties (see Stevenson 1985). Examples of fulvic acid structures are shown in Fig. 11 (Leenheer *et al.* 2004).
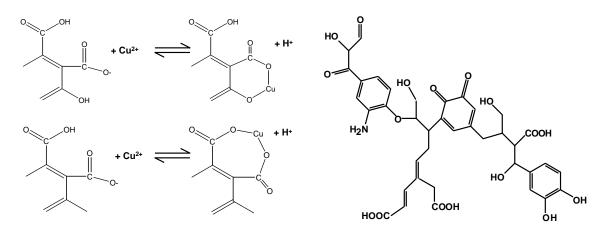

Figure 10. Left: Complexation reactions proposed to account for ion exchange capability of humic acids, involving either a phenolic OH and a carboxylate group or two carboxylate groups; Right: Representative structure of a humic acid, as proposed by Sevenson (1985).

Humic substances are generally resistant to biodegradation. For example, it has been reported that in soil they degrade at a rate of 2 to 5% per year (Linhares and Martin 1978). However, some enzymes have been found to degrade humic substances at an accelerated rate. Hurst *et al.* (1962) were among the first to demonstrate the decolorizing effects of the *T. versicolor* and *Hypholoma faciculare* white rot fungi. Hoffrichter *et al.* (1998) found that the enzyme MnP was the key enzyme in the degradation of humic substances. Substantial humic acid degradation was observed by Steffen *et al.* (2002) using MnP enzymes. Forest litter and layers of humus in the forest have been reported to degrade at an almost visible rate in the presence of white rot fungi (Steffen *et al.* 2002). The degradation of humic substances, involving enzymes such as LiP, MnP, and laccase, has been attributed to extracellular, non-specific enzyme activity (Kästner and Hofrichter 2001).
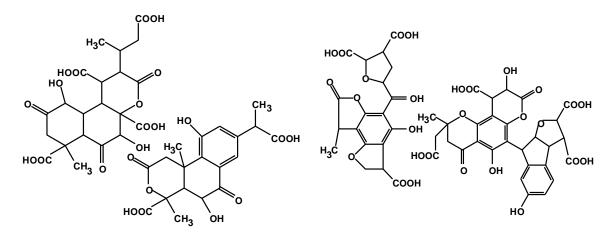

Figure 11. Fulvic acid examples, as isolated and characterized by Leenheer et al. (2004)

The water-holding ability of humus can be at least partly attributed to the acid groups, which in their dissociated state bear a negative charge. Humus also affects the texture of soils, a factor of great importance from the perspective of roots, worms, and other things that need to make their way in the soil environment. Though none of the cited studies has demonstrated this point, it is also reasonable to expect that the presence of difficult-to-degrade organic material can provide a "timed release" characteristic to soils, such that a moderate amount of additional oxidation can take place by slower biochemical processes.

BIOLOGICAL DECOMPOSITION RATES OF SOIL AMENDMENTS

Management of soil organic matter (SOM) is important for soil productivity and for the responsible utilization of crop residues for additional uses. The CQESTR model, pronounced "sequester", a contraction of "C sequestration" (meaning carbon storage), is a process-based soil carbon balance model that computes biological descompostion rates of crop residues or organic amendments as they become converted to SOM. Soil carbon models are useful for examining the complex interactions between climate, crop, and soil

management practices and their influences on long-term changes in SOM or soil organic carbon (SOC). The C model CQESTR was developed by USDA-ARS (United States Department of Agriculture-Agricultural Research Service) scientists at the Columbia Plateau Conservation Research Center (Pendleton, Oregon, USA). The model has been used for field-scale evaluation of SOC stocks (Gollany et al. 2010; Liang et al. 2008, 2009; Rickman et al. 2002). The model operates on a daily time-step and performs long-term (100-yr) simulations. The carbon pools are depicted as a continuum. The basic model structure and carbon flow in the CQESTR model are illustrated in Fig. 12.
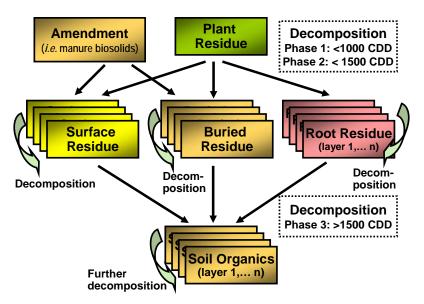

Figure 12. Carbon flow at the CQESTR model (Gollany et al. 2010; Liang 2008; Rickman et al. 2002)

Decomposition of organic material can be understood as a three-phase process. After each placement of residue in the soil, decomposition occurs in two phases. Phase I is a rapid phase covering the first 1000 cumulative degree-days (CDD or thermal time), approximating the oxidation of readily metabolizable substrate. Phase II is a slow decomposition phase, representing oxidization of more recalcitrant materials. Crop residues and organic amendments are categorized by their placement in the soil, and their identities are maintained during the two phase of decomposition. Each organic residue addition is tracked separately according to its placement within distinct soil horizons. After 15,000 CDD when Phase II is complete, the composted residue is transferred to the stable SOM pool (Phase III) (Liang et al 2009).

The decomposition model used is as follows,

$$R_{r,j} = \begin{cases} R_{p,j} * \exp[k * fN_j * fW_j * fB_j * fX * fD * CDD_j]; & CDD_j < 15000 \\ 0; & CDD_j \geq 1500 \end{cases} \quad (2)$$

where

$R_{r,j}$ = Residue or organic amendment j <u>r</u>emaining at the end of each decomposition time step (weight/area)

$R_{p,j}$ = Residue or organic amendment j at <u>p</u>revious time step (w/a)

k = Universal decomposition rate constant, °C^{-1} d^{-1}

fN_j = <u>N</u>itrogen content factor for residue j

fW_j = <u>W</u>ater availability factor for residue j

fB = <u>B</u>iomass type factor

fX = Soil <u>t</u>exture factor

fD = Soil <u>d</u>rainage factor

CDD_j = Cumulative degree days of residue j for this time step, °C d
(with a base temperature of 0 °C).

The CQESTR Model: SOC Budget Algorithms

The total soil organic C budget can be represented by Eq. (3) using units of dry weight per unit area within each soil layer,

$$TOC = (C_{SOM} - C_{DOM}) + \sum^{u}(C_{S,\,l} - C_{DS,\,l}) + \sum^{v}(C_{R,\,m} - C_{DR,\,m}) + \sum^{w}(C_{A,\,n} - C_{DA,\,n}) \qquad (3)$$

where TOC = Total SOC; C_{SOM} = carbon in the stable SOM; C_{DOM} = decomposed organic matter lost as carbon dioxide (CO_2); $C_{S,l}$ = carbon in shoot residue l; $C_{DS,\,l}$ = carbon lost as CO_2 from decomposed shoot residue l; $C_{R,\,m}$ = carbon in root residue m; $C_{DR,\,m}$ = carbon lost as CO_2 from decomposed root residue m; $C_{A,\,n}$ = carbon in organic amendment n; $C_{DA,n}$ = carbon lost as CO_2 from decomposed amendment n; u, v, w = all applications of organic materials from the initial time to the current day. The CQESTR model can be used to predict and evaluate soil organic matter or soil organic carbon changes from various agricultural management practices.

PLACING A VALUE ON COMPOSTING

Given the increasing worldwide demands for various kinds of biomass, it is worth considering under what circumstances composting can be regarded as the highest-value use of a given lignocellulosic material. The oxidation of cellulose that accompanies composting sometimes might be judged as a needless waste of potentially capturable heating energy. In essence, one may need to choose, in a given instance, whether it is more advantageous to let lignocellulose material rot naturally, to compost it under controlled conditions, to use it to make bio-based products, or to use it in the form of fuels to displace some usage of petroleum resources. On the other hand, the processes taking place within composting may be so essential to life itself that the ecosphere benefits measurably by human efforts to assist the process. Questions like these will require further study. Nevertheless, published articles, as summarized below, shed some light on the environmental sustainability of various composting practices.

Waste Handling

A first set of arguments in favor of widespread implementation of composting practices is that they address urgent issues related to safety and quality of life. In effect, one makes the claim that planned and optimized rotting of bioresources is substantially safer and more beneficial than uncontrolled or even misguided rotting – as might occur due to a society's lack of knowledge about alternatives to mainstream practices, including maybe too much reliance on municipal wastewater treatment, waste sludge disposal in landfills, and also the landfilling of lignocellulosic materials. Research is needed to ascertain whether lignocellulosic materials handled in an optimized composting process can result in less release of greenhouse gases than when the same materials are placed in a typical landfill, for instance. Certain composting practices have the potential to displace highly objectionable release of such gases as methane, nitrous oxide, and ammonia (Bonneau *et al.* 2008). Also, there are significant opportunities to minimize production of odorous compounds, compared to landfilling of organic wastes (Zigmontiene and Zuokaite 2010).

Though composting of lignocellulosic wastes tends to produce carbon dioxide, studies related to the life cycle options for such waste have shown more favorable results of composting relative to conventional landfilling (Pikon and Gaska 2010). Kim and Kim (2010) showed that one ton of food wastes resulted in 1010 kg of CO_2 equivalents from landfilling, but only 123 kg of CO_2 equivalents if the same waste was composted. Zhao *et al.* (2009) found in the case of kitchen wastes that the overall production of greenhouse gases could be reduced significantly by composting.

Soil Productivity

Another argument in favor of more widespread implementation of composting practices, especially if they are carried out at a large scale, is they may reverse damage done by overzealous usage of synthetic fertilizers. As noted by Moss *et al.* (2002), the "green revolution" of the 1940's, which greatly increased world food production, was not green in a modern sense. The non-renewable petroleum-based fertilizers associated with the green revolution displaced earlier widespread use of manures and human wastes (traditionally called night soils), and some of these wastes subsequently have not been put to meaningful use (Golueke 1972). Especially in cases where biomass such as sawdust or bark are already being accumulated at a centralized site, one can consider the value of those materials as a compost component. Unless there is a higher-value usage identified, the enhancement of soil productivity (Kostov *et al.* 1991; Rantala *et al.* 2000; Lalande *et al.* 2003) can be counted as one of the key arguments in favor of using those resources in compost. Comprehensive life-cycle analysis work will be needed in the future to sort out some of these issues.

Losses

Another part of the equation, in attempting to justify emphasis placed on widespread implementation of composting practices, concerns the inherent inefficiency of composting from an energy standpoint. An analogy can be made to commerce. Buying an item in a traditional market system might involve a long chain of different intermediate vendors, each of whom spends a lot of time haggling prices with the next

person to temporarily hold that item and attempt to sell it to the next level of intermediate vendors, then eventually to an end customer. The price paid by the final customer has to be sufficient to support the families of all of the intermediate vendors. There is a huge potential for profit if some entity can directly connect the makers of items with the end-users. The analogy is not perfect, but one has to wonder about the successive populations of bacteria and fungi that need to grow and then themselves be consumed (Atkinson *et al.* 1997), only to produce an end-product that has much lower fuel value than the starting material.

Solid mass loss during composting

From a waste-handling perspective, reduction of mass is often considered as a key benefit of composting (for instance, see Alberquerque *et al.* 2009). But from the perspective of creating a component for soils, a higher yield might be considered as a better outcome, as long as the product still meets expectations.

The Polluting Nature of Compost

Another set of arguments that future life-cycle analyses will need to consider is whether the compost itself contributes significant pollution. Many such issues may be associated with the decisions regarding whether a given compost batch has been sufficiently matured for the application; in other words, has the composting process been completed? Clearly there is potential for more substantial odors, leachate, or toxic effects in cases where the biological processes within compost are still highly active. Certain individuals are allergic to certain composts (Dickson *et al.* 1991). Presumably such effects would tend to be reduced as the content of microbes and enzymes in compost declines during the maturation process.

ALTERNATIVES TO COMPOSTING AND RELATED PRACTICES

When considering the best use of a given biomass resource, composting also should be compared versus a number of alternative processes, some of which have similarities to composting. For example, some of the same lignocellulosic materials that are often used in compost recipes also can be considered as feedstocks for production of liquid fuels (Taherdazeh and Karimi 2007a,b; Hu *et al.* 2008).

Another alternative is to use composting as the first stage of another process; thus Barneto *et al.* (2009) evaluated the effect of precomposting biomass before gasification. Such a practice might be justified based on a higher yield of lignin gasification, in comparison to gasification of raw biomass. In this context, composting can be viewed as an inexpensive way to increase the proportion of lignin-like content in feedstock for gasification. It would be interesting to consider a fuller life cycle analysis of the process, also taking into account yield loss during composting, not just during gasification.

Instead of focusing on the production of compost, the process can instead be optimized for the production of enzymes or the microbial populations that produce needed enzymes. Alternatively, it is well known that material from the active phases of composting can be used either to accelerate the composting of freshly built piles or to

help biodegrade specific materials (Czaja-Jagielska and Domka 2007). The concept is closely related to the use of activated sludge during secondary treatment of wastewater (Seviour and Blackall 1999).

Direct Addition of Biomass to Soil

Questions also should be raised as to the relative merits of composting *vs.* direct addition to soils (Martin-Olmedo and Rees 1999; Whalen *et al.* 2000; Kelleher *et al.* 2002; McGinn and Sommer 2007). One may argue that biodegradation of the material can take place in either case, and direct soil addition sometimes may involve less labor. Work by McGinn and Sommer (2007) indicated that composting has the potential to decrease the net amount of ammonia emulsions from a given amount of manure. However, further work is clearly merited to determine any overall benefits that might accrue from, for instance, the higher temperatures associated with composting, as opposed to near-ambient temperatures usually associated with direct land application.

Lignocellulosic material also can be used as mulch. Covering of soil with mulch can provide such benefits as control of weeds, reduction of evaporation, and moderation of soil temperature (Dickson *et al.* 1991).

Production of H_2, CH_3, and NH_3 from Biomass (Anaerobic Processing)

Depending on conditions such as air supply and pH, processes similar to composting can be optimized for the production of potentially valuable gases and related products. For example, anaerobic conditions can be used when the objective is to obtain hydrogen from waste matter (Van Ginkel *et al.* 2001; Ohmiya *et al.* 2005; Chou *et al.* 2008; Lee *et al.* 2008). Chou *et al.* (2008) found optimum conversion to hydrogen, in addition to fatty acids and alcohols, at pH=6 in the presence of moderate (laminar) stirring. Sadaka and Engler (2003) obtained major quantities of methane when composting animal manure under unfavorable conditions of biodegradation.

Various authors have considered the optimization of composting conditions to enable collection of NH_3 gas and related products (Eiland 2001a,b; Bock 2004; Hong and Park 2005). Eiland *et al.* (2001b) showed that composting of liquid swine manure could be carried out in a closed system, allowing NH_3 gas to be collected. Raising the pH tends to promote the release of NH_3 (Recovery Systemss, Inc. 2005; see also Saludes *et al.* 2008). The ammonia then can be stripped in a phosphoric acid reactor, after which the ammonium phosphate can be sold as a valuable nutrient, well suited for phosphorus-poor soils. Veeken *et al.* (2004) developed a system in which pig slurry was separated into liquid and solid fractions. The liquid fraction was concentrated by evaporation, during which the released NH_3 was scrubbed with nitric acid, yielding ammonium nitrate, a valuable fertilizer. Liang *et al.* (2000) describe a bioreactor capable of capturing NH_3 and converting it to a more stable nitrate form. Hong and Park (2004) showed that boric acid in the presence of wood chips could be used to trap and bind ammonia that had been generated by the decomposition of pig wastes.

Production of Ash

Another potentially beneficial use of waste biomass is to incinerate it and collect the fly ash. Such ash can be valuable as a source of KOH (Beck 1997). Thus, Bock

(2004) obtained ash from combustion of biosolids from processing of swine manure slurry, in addition to turkey litter. The ash was then reacted with phosphoric acid, yielding a shippable product to be used in soils deficient in potassium and phosphorus. Fly ash also can be used to prepare sites for windrow composting (Webber *et al.* 2009). The cited authors showed that the fly ash tended to reduce the loss of phosphorus from the compost piles resulting from liquid runoff during rainy periods.

Production of Surfactants

Montoneri *et al*. (2008) found that composting of urban green waste yielded products displaying a lower critical micelle concentration (CMC) and lower surface tension in water, compared to the initial compost mixture. Both of these observations are indications of effectiveness as a surfactant mixture. Thus, in principle, biobased surfactants could be collected as a co-product of composting.

CONCLUDING REMARKS

Studies related to composting appear to have much to teach those who are interested in the decomposition of cellulosic materials. Interest in biodegradation is widely shared, including by those who study wooden structures, as well as by those who want to break down wood to obtain liquid fuels or other chemicals, for instance. Further advances in science can be expected to help in all such applications.

It is heartening to learn that despite some progress in mechanization, composting is still by and large "natural" from the standpoint of the decay process, meaning that most of the materials can be part of a sustainable cycle. Value provided by composting operations includes the relatively safe and cost-effective handling of organic wastes, as well as the production of a beneficial amendment for soils. Whether or not composting is the best or most appropriate usage of a given lignocellulosic resource will need to be considered on a case-by-case basis.

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