Odor in Commercial Scale Compost: Literature Review and Critical Analysis

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Odor in Commercial Scale Compost

Literature Review and Critical Analysis

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Table of Contents

List of Figures and Tables

Page

Figures

Page

Tables

Executive Summary

Managing residual organics in cities has been a major sustainability challenge of every historical civilization, with negative impacts ranging from nuisance odors and inefficient resource use to serious human health and environmental consequences. In spite of the technological progress achieved in recent decades, managing organic residuals remains a significant challenge, particularly as more programs have been established to recycle highly biodegradable food scraps. For reference, in 2008, food losses were estimated to be 30% at the retail and consumer levels in the U.S., with a total estimated retail value of $165.6 billion (Buzby and Hyman, 2012). An estimated 1 million tons of food is landfilled in Washington State annually (WA Ecology, 2010a), contributing to greenhouse gas emissions and many other environmental concerns. Diversion and composting of Washington State's food scraps would reduce greenhouse gas emissions by 872,695 metric tons of carbon dioxide equivalents (CO_2e) annually, representing 1.8% of Washington State's target emissions reduction by 2050 (U.S. EPA, 2011).

While we have a long way to go, we can take pride in the fact that Washington State leads the U.S. in implementing food scrap "recycling". We have approximately 60 municipal organics recycling programs, which is roughly equal to California and many more than other states (Yepsen, 2013). Most of these programs have been established within the last decade, and other communities express ongoing interest in continuing this trend.

However, successful development of organics recycling has had challenges, particularly when food scraps are diverted to composting facilities designed primarily to process green waste. U.S. cities including Seattle, Portland, Philadelphia, San Francisco, and Waukegan (IL) have grappled with odor and air emission concerns due to increased flows of highly putrescible food scraps to composting facilities (Le, 2013; Driessen, 2013; Allen, 2013; Howard, 2013; Moran, 2013). Because of the time lag between residential disposal, collection and transport, food scraps have often begun rotting prior to arrival at the compost facility. When rotting food scraps are combined with increasing fresh green waste flows in late spring through early summer the potential for odor generation dramatically increases.

In addition to these obvious odor problems, recent studies from Swedish researchers (Sundberg et al., 2004), the U.S. Environmental Protection Agency (US EPA, 2008), and the U.S. Compost Council (Christiansen, 2009) demonstrate that inclusion of partially decomposed food scraps can lead to acidification and inhibition of standard composting, resulting in poor compost process control and inferior product stabilization. Operation under such conditions leads to the increased release of volatile organic compounds (VOC's), methane, and ammonia – all potential sources of potent odors and other emissions harmful to the environment and human health. These studies further indicate that standard compost management strategies (increasing temperature and air-flow) designed to reduce odor problems under normal composting conditions may, in fact, aggravate the odor problems.

There are many possible ways to reduce odor from food scrap composting. Strategies fall generally within four categories:

- Enhancing emissions control infrastructure (e.g. more air quality control equipment),
- Biological optimization of compost piles (e.g. changes in size, aeration, etc.),
- Adding anaerobic pre-processing for the highly biodegradable wastes (e.g. high solids anaerobic digestion), and
- Amending compost materials with high-carbon products (e.g. biochar).

It is important to recognize that each of these strategies potentially involves greater levels of complexity, control and training for personnel, as well as increased capital and operating costs. Thus, evaluating which strategies should be used requires technical and financial assessment specific to the facility and odors problems, the business model and technical capacity, and community priorities.

Among major strategies, non-biological structures, technologies and controls can be implemented throughout the compost production process. Some of the most important for controlling odors include next generation negative-air tipping buildings, covered structures as well as covered piles for the actual compost operation, use of multiple, staged biofilters, and more rigorous design and engineering of facilities.

Second, biological approaches, both stand-alone or in conjunction with the other general strategies, can be a powerful methodology to enhance the composting process and improve control of odor. These methods are particularly important for ensuring that the first phase of composting is not delayed by lowered pH and that aerobic processing is maintained. In particular, staying within recommended targets for aeration, oxygen content, moisture, temperature, pile size, bulk density, C:N ratio, and seeding rate is likely to be critical. Real-time process controls that monitor pile conditions and respond by adjusting aeration or other mechanisms are also likely to be important. Strongly related to this is ensuring that proper mass flows are maintained within the facility. This is important, as it is not uncommon for compost facilities to accept too many wastes. Higher than preferred flow rates can lead to management changes that negatively impact the biology and contribute to odors. These problematic management changes can include increasing pile size, maximizing temperature, and reducing the frequency of pile turnings. Research has shown that with food scraps and other putrescent material, these management changes will only exacerbate the tendency for piles to acidify, become anaerobic, and release additional odors.

Third, a small but clear body of literature indicates important environmental benefits that could result from integrating anaerobic digestion prior to composting, specifically for the treatment of highly biodegradable food scraps and fresh grass clippings. This could reduce odors, improve air quality, enhance organic recycling processing quality and performance, and reduce greenhouse gas emissions. Because the process also generates energy in the form of a biogas, it could help offset the energy needs of the composting operation. Remaining hurdles include improving technical performance for digestion of highly biodegradable wastes, and added costs and complexity of such facilities. Most importantly, continued improvements need to be made to improve the economic viability of commercial projects. Further research could lead to advances in anaerobic digestion technology that could reduce costs, increase performance, or develop value-added co-products. Using the biogas to produce liquid fuel rather than electricity may be more economically viable for recycling facilities with large fleets of collection trucks.

The fourth major odor-control strategy includes incorporation of carbon-based materials to piles, including activated carbon, high carbon wood ash, and biochar. Among these, activated carbon is generally understood to be technically effective but too expensive for widespread use in compost odor control. High carbon wood ash is a waste product from biomass energy combustion, and is therefore obtainable at relatively low cost. The small amount of published scientific literature on high carbon wood ash indicates mixed results. The product may provide some composting process benefits (e.g. faster processing, higher initial temperatures), and may reduce some odors, but may have no impact on or may even increase others. In addition, at higher quantities, the ash may compromise the quality of the compost as a plant growth medium.

Meanwhile, research results are beginning to show how biochar can improve compost processes and reduce methane emissions. Biochar can hold air and water at the same time, encouraging aerobic bacteria and reducing the number of anaerobic pockets that produce methane, potentially reducing odors. It also appears to support denitrifying organisms in ways that reduce the production of nitrous oxide, a potent greenhouse gas. Biochar can improve compost quality by retaining nitrogen and other nutrients and minerals. It promotes compost maturity and increased humification and may have positive climate impacts as more carbon is converted to stable humic substances. Recent studies suggest that biochar compost may be high quality, with positive effects on plant growth.

There are a number of ways that biochar could be used in current composting systems to reduce the generation and propagation of odors. These include adding it to anaerobic collection bins to suppress volatile fatty acid generation, using it in compost receiving areas for immediate odor control, and using it as cover or a bulking agent in windrows. Biochar may also work to extend the life of biofilters and control leachate in compost yards. At this time there is very limited economic analysis available for the use of biochar as an odor control strategy. Any economic analysis of using biochar in compost should balance the cost of using biochar against increased returns from the sale of higher quality compost than is obtainable without biochar.

It is clear that there are many approaches that could be used by the industry to reduce the odors presently associated with aerobic compost treatment of organics enriched in food scraps and fresh yard clippings. For existing compost facilities, enhanced design criteria, in-time process monitoring with feedback control, and changes to maximum flow rates and processing times are some of the factors that will need to be considered in potential updates to management plans to more adequately address odor problems in the near-term. In the longer-term, integration of next generation process technologies such as high solids anaerobic digestion and pyrolysis / biochar may be more advantageous due to the greater potential environmental and human health benefits, more effective treatment of highly biodegradable waste streams, potential for renewable energy generation, and even the potential economic viability of organic materials recycling facilities.

Introduction

Background

Currently, 54% of United States (US) and 45% of Washington State (WA) municipal solid waste (MSW) is landfilled (U.S. EPA, 2008; WA Ecology, 2010b), a costly and unsustainable strategy. To address this, many communities are encouraging per capita reductions in MSW generation and increases in waste recycling and diversion. Diversion has been a particularly effective strategy for green waste, with 64.1% of this large category (21.1% of total US MSW) being diverted towards compost production. Many municipalities and other communities in the US are looking to develop a similar success story with food scraps through diversion to similar composting facilities. Within the US the number of municipalities with source separated food scrap collection has grown from a total of 24 in 2005 to 183 in 2012, now serving 2.55 million households (Yepsen, 2013).

Like green waste, food scraps are a large category of waste. Globally, the United Nations reports that about 1.3 billion tons of food is lost or wasted annually. This is equivalent to one third of world annual food production (Nellemann et al., 2009). Likewise, in the US, Buzby and Hyman (2012) estimated that 30% of all food was lost at the retail and consumer levels, representing a total estimated retail value of $165.6 billion. Food scraps comprise 12.5% and 18.0% of US and WA MSW respectively, with diversion estimated to be just 2.6% and 8.0%, respectively (U.S. EPA, 2008; WA Ecology, 2010b).

Diverting food scraps can create environmental benefits compared to other options, though relative impacts depend on method of processing, distance of facilities from waste generation sites, and other factors. Using a life cycle analysis (LCA), Kim and Kim (2010) demonstrated that the cradle to grave global warming potential of landfill disposal of food scraps is nearly eight times higher than either composting or animal feed diversion. Similarly, Lundie and Peters (2005) showed that landfill disposal of food scraps had much greater climate change impacts than in-sink food scrap processing or centralized composting. However, their analysis also indicated that in Sydney, centralized composting required more energy than other treatment options, due to the frequency of collections (two collections systems for MSW and green waste operating in parallel on a weekly basis) and the small quantities of waste collected per household.

Diverting food scraps can also provide economic benefits. A 2001 California study estimated that diversion and recycling of material nearly doubled the local economic impact relative to landfilling that same material (Goldman and Ogishi, 2001). A Seattle study found that food scrap collection and diversion programs reduced costs by 20% compared to landfilling (Bloom, 2011). This conclusion is also site-specific as a study by Houssaye and White (2008) for collection of food scraps from New York City found that diversion from landfill to compost represented a potential slight increase in treatment costs ($105-$160 for landfilling versus $113-$233 for composting). However, this cost difference was due to long-haul transportation costs to distant compost sites, representing as much as 22-36% of total costs.

Food scrap recycling also has drawbacks. Most food scrap recycling utilizes existing green waste composting facilities, thus increasing the processing burden on existing infrastructure. And as increasing percentages of putrescent food scraps have been added to the existing processing stream of woody and green biomass, concerns have emerged about odors (Kim and Kim, 2010; Sundberg et al., 2011) in these communities, among others:

- Seattle, WA, Cedar Grove (Le, 2013);
- San Francisco California, Jepson Prairie (Howard, 2013);
- Rikers Island, New York City New York (Rao, 2013);
- Portland Oregon, North Plains (Driessen, 2013);
- Philadelphia Pennsylvania, Philly Compost (Allen, 2013);
- Waukegan Illinois, Nu-Earth Organics (Moran, 2013).

Compost operation

Composting is a biological process utilizing controlled, aerobic conditions and a mixed ecology to produce compost, a valued soil amendment. Finished compost by definition has undergone an initial, rapid stage of decomposition; a longer stage of stabilization; and ultimately an incomplete process of humification (Insam and de Bertoldi, 2007). The specific phases of the process are:

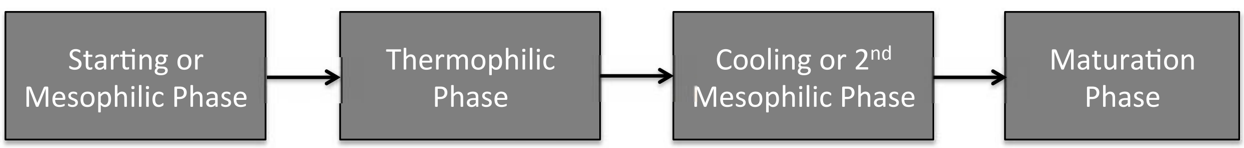


Figure 1.1: Composting steps (Insam and de Bertoldi, 2007)

The mixed ecology is comprised of primary decomposers in the first stage, including fungi, Actinobacteria and bacteria, with three orders of magnitude higher levels of mesophilic inoculums (those that grow best at moderate temperatures) as compared to thermophilic (high temperature). However, active decomposition and resulting exothermic processes lead to a continual temperature rise, which induces shifts in population towards thermophilic populations during the second stage. Temperature continues to rise gradually, from 35ºC to roughly 62ºC (Insam and de Bertoldi, 2007). Continued temperature elevation to as high as 80ºC can occur with Insam and de Bertoldi (2007) attributing this to abiotic exothermic reactions. Consistent temperatures are difficult to maintain across an entire compost pile, though better uniformity can be achieved when effective turning and/or other mechanisms to promote active aeration are used. Eventually, the temperature range falls below the thermophilic range, inducing a second mesophilic range as readily degradable organic compounds are exhausted. Re-colonization with mesophiles results from either surviving spores residing within low-temperature microclimates within the pile or through active re-seeding. In the final maturation step, bacterial populations decline rapidly while fungi populations increase, producing a final product that is primarily composed of recalcitrant lignin-humus complexes.

Odor

Odors are the result of specific compounds that can be produced before materials arrive at the compost yard, during compost handling and preparation, or during actual composting. Compounds primarily responsible for odors appear to be organic sulfides, mercaptans, amines, and volatile fatty acids (VFA) (Miller, 1993; Goldstein, 2002). Terpenes, ammonia, alcohols, and hydrogen sulfide can also contribute (Epstein, 1997). Most of these compounds are intermediates and/or reduced in chemical state. Thus, their accumulation and release to the surrounding air is generally the results of one of two causes. It may be a manifestation of a series of interrelated biological steps that has become discordant, such as a precursor step occurring at a production rate that overwhelms a follow-up step. Or it may be an indication of inadequate controls on air flow (oxygen) rates, either during pre-processing or actual composting, which leads to premature, over-concentrated, and/or wide dispersal of odorous compounds. A number of factors control the production and release of these odorants. Below is the summary of key factors of reviewed in more detail in IWMB (2007):

- *Feedstock*: Compost inputs with high protein content are particularly vulnerable to production of odorous compounds. Proteins are made up of amines, which contain and may release volatile nitrogen (amines and ammonia) and volatile sulfur (organic sulfides, mercaptans, and hydrogen sulfide). Feedstock with high amine and protein content include poultry manure (0.56% dry weight (DW)), biosolids (0.3-1.2% DW), food scraps (0.4% DW), and green waste (0.3% DW) (Miller, 1993). In addition, feedstock containing high percentages of carbohydrates, fats and oils degrade quickly, often producing VFA. This is especially the case under low-oxygen conditions.
- *Nutrient Balance and Elemental Ratios*: Effective composting is generally conducted at carbon to nitrogen (C:N) ratios near 20-25:1 and carbon to sulfur (C:S) ratios of 100:1 (Miller, 1993). Significant deviations from these ratios, high or low, negatively impact the compost operation and increase the likelihood of producing odors. Maintenance of these preferred ratios is primarily achieved by feedstock choice and feedstock mixing, although it is important to note that monitoring of ratios is a simple and straight forward mechanism to maintain quality control and can be important in determining what agents or additives could be used (see subsequent chapters).
- *Oxygen*: Most odorous compounds simply do not develop or are quickly converted to more innocuous compounds when there is sufficient oxygen supply. Thus, it is important to maintain aerobic conditions. Hydrogen sulfide, organic sulfides and VFA only form under anoxic/anaerobic conditions. These are the three most common and important compounds or classes of compounds that cause odors. As discussed in the ensuing sections, effective oxygenation is strongly related to feedstock type, aeration rate, pile size and temperature.
- *Aeration*: The primary effect of aeration is the maintenance of desired oxygen levels. However, most actively aerated systems utilized by large compost operations also control high temperature through aeration. This simultaneously moderates moisture levels. Another side effect is that potentially odorous intermediate compounds, such as ammonia, are released to the bulk air and dispersed prior to utilization by the pile microbes.

- *Time*: Odor-causing compounds are not produced evenly over time in compost piles. Food scraps are degraded and odors are already extensive when highly degradable feedstocks are delivered to the compost yard. And the pile heats quickly during the mesophilic stage, particularly when highly biodegradable feedstock is present. This is especially true when decomposition of the food scraps causes anaerobic conditions to develop. Thus, the greatest quantities of odors are released during this first stage, approximately 3-14 days (Epstein, 1997). Notably, this odorous period can be lengthened if biological inhibitions delay the composting process (Sundberg et al., 2011).
- *Moisture*: High moisture levels can lead to narrow or filled pore spaces between particles in a composting pile, inhibiting both passive and forced aeration and ultimately the supply of oxygen. This can delay the composting process and create anaerobic conditions. It then can lead to the production of odorous compounds, though numerous other factors including feedstock are also important. High moisture can be particularly troublesome in Pacific Northwest Coastal Areas and other wet regions due to precipitation mixed with incoming food stocks and falling on open piles. While excessive moisture (>60%) is undesirable (Wilber and Murray, 1990), too little moisture, which can be exacerbated by poor pile mixing or poor aeration/temperature maintenance, is also bad. This is because a moderate level of moisture is required to maintain effective biological activity.
- *Bulk Density/Porosity*: Air movement is reduced as bulk pile density increases. Bulk density is related to moisture as wet particles are denser. Bulk densities of 1,000 pounds per cubic yard or less (Oshins, 2006) are desired though this depends upon the type of feedstock. Grass clippings and food scraps are notable for having small particle size, high density, and high moisture content with rapid release of internal water to the bulk pile. These can all increase bulk density, necessitating close monitoring and control of bulk density through the compost process (Buckner, 2002).
- *Temperature*: Biological activity and rate of decomposition increase with increasing temperatures up to 60-65°C (140-149°F). Thus, if other factors such as aeration, moisture, bulk density, etc. are adequately controlled, use of elevated temperature up to 65°C can hasten the biological processes and help control odors. However, debate continues regarding the viability of composting above 65°C as several species do not thrive at these high temperatures (Epstein, 1997; Insam and de Bertoldi, 2007). Temperature, like aeration, allows for greater volatility of odorous compounds. So while it does not specifically contribute to generation of odorous compounds, it can increase odor dispersal and impact.
- *pH*: Maintaining a proper acid-base balance of the compost is vital for controlling odors. Deviation from a neutral range (6-8), either lower or higher, results in reduced biological performance and higher likelihood of producing odorous compounds. In particular, readily biodegradable materials such as grass clippings and food scraps are prone to producing a low pH (acidic) environment that results in VFA, alcohols, and hydrogen sulfide. Acidity kills off beneficial organisms and leaves acid-tolerant and odor-generating species to predominate. This results in greater acidity, reinforcing the cycle and deceasing compost production and product quality (Sundberg et al., 2011). This biological interaction is discussed in detail in future chapters.

Report overview

Greater diversion of food scraps and other organics from the residential and industrial food resource sectors is placing pressure on existing organics processing infrastructure dedicated to aerated compost treatment. This has led to community concerns related to odor management. As a first step to resolving emerging odor concerns, Washington State University (WSU) has been asked to provide a broad review of academic and popular press literature that describes existing attempts to control odors within large-scale, actively aerated compost operations treating significant percentages of fresh green waste and food scraps. This report summarizes:

- Non-pile, infrastructure approaches *(Chapter 2)*;
- Non-anaerobic, biological approaches to pile management *(Chapter 3)*;
- Anaerobic approaches to treatment of the highly biodegradable fraction of MSW *(Chapter 4)*; and
- Use of amendments for pile physical/chemistry/biology management *(Chapter 5)*;

The conclusion provides a critical summary and analysis of the detailed literature reviewed.

Non-Pile, Infrastructural Approaches to Odor Management

Background

This section focuses on the facility design, equipment and mechanical operations that can control odors. Large municipal compost facilities use numerous processing steps, buildings, and complex machinery to produce finished compost for market. Figure 2.1 describes major operations, their order, and interconnections. It also indicates potential odor release points.

While facilities may vary slightly in their setup, key steps or features that are common to all facilities include (1) a receiving/tipping/storage building; (2) biofilter and/or gaseous treatment technology; (3) outside handling/pre-processing steps; (4) composting pile (5) liquid storage tanks/ponds from leachate and storm water; (6) product curing and storage; and (7) site footprint/offset. Each of these key components will be reviewed within this chapter.

Winges (2011) analyzed the contributions of facility unit operations to odor production at Cedar Grove Composting (Seattle, WA). The vast majority of odors resulted from outside handling of materials and the compost piles, indicating that these steps should be targeted for overall odor abatement (Table 2.1). Consistent with earlier discussions, the primary pile generated 83% of the odors from piles—this despite an odor controlling cover.

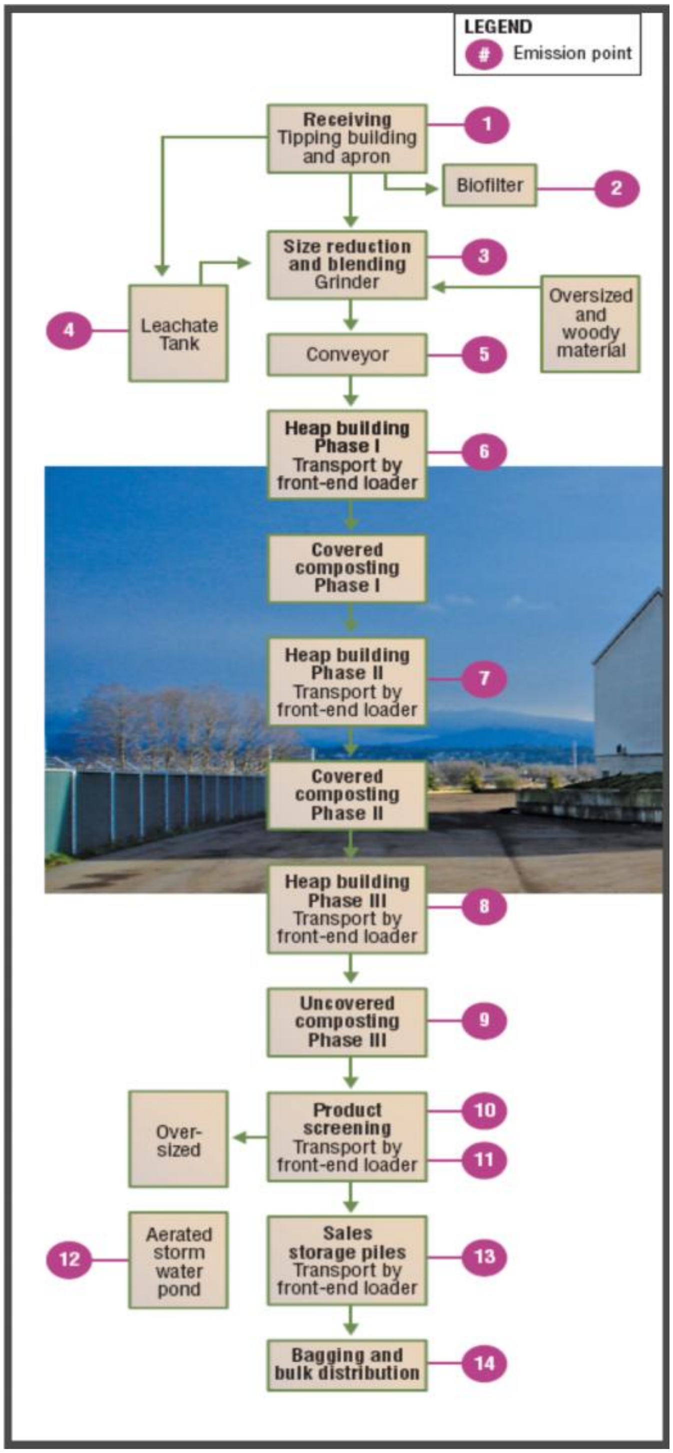


Figure 2.1: Compost schematic

Table 2.1: Relative percentage of odor flux per unit operation (Winges, 2011)

Unit Operation	% Total OU/s
Receiving/Tipping Building/Biofilter	5.2
Outside Handling (grinding, conveyer, building piles, turning piles, screening)	32.9
Piles (Phase 1 and Phase 2 piles covered, Phase 3 piles not)	48.0
Ponds/Leachate	3.3
Storage/Product	4.2
Miscellaneous	6.4

OU = odor unit

Receiving/Tipping/Storage building

Food scraps and green waste (e.g. grass clippings) can often enter the compost yard already partially degraded, putrescent and releasing significant odors. This is caused by the times associated with actual food scrap production, source separation, collection, and transport—meaning that several days may pass before arrival at the compost facility, a time more than sufficient for natural biodegradation and putrescence. As a result, it is imperative that receiving/tipping buildings be constructed so as to minimize the impact of these immediate odors during initial storage and processing. Many new urban compost facilities that treat food scraps are using receiving buildings with advanced design for first stage control of noxious odors (Goldstein, 2013).

First generation receiving buildings are completely enclosed structures with negative air pressure. This negative air pressure contains odors that otherwise might be released when large doors are opened to receive and load material. Many first generation buildings are too small or poorly designed, causing much of the loading and mixing to occur outside on mixing pads that have minimal or no air control. In addition, their design also generally lead to ‘first in, last out’ processing as opposed to ‘first in, first out’ processing. This means that some material decomposes over an extended period prior to processing, allowing for odor production.

Next generation buildings are larger and have greater air handling capacity so that receiving, loading, mixing, and seeding can all be accomplished under negative air pressure. The extended size and design also allows for more effective movement of material, and ‘first in, first out’ processing (Goldstein, 2012; Pacificlean, 2013). An emerging trend in wet climates is to cover the entire compost operation. Normally, these are windrow or aerated static pile systems under covered structures, primarily clear-span type facilities (Goldstein, 2012; Goldstein, 2013; Tucker, 2013). Silver Springs Organics (Rainier, WA), Laurelbrook Farm (East Canaan, CT), St. Louis Composting (Belleville, MO), and LHF Compost (Peoria, IL) are just a few examples of these operations. Coast Environmental (Victoria, BC), has taken the approach to the next level, providing a ‘contained within container’ approach that utilizes both synthetic covers to piles and a covered structure over those piles (Goldstein, 2012). Cost analyses in relation to improvements in composting operation, quality and odor release must be completed for these emerging strategies.

Some facilities have adopted the following additional best management practices (BMPs). First, some negative air buildings have installed aeration systems within the floors of the building so that biological processes can begin immediately to control acid chemistry and release of odors. The additional floor aeration accentuates airflow to the biofilters (Coker, 2012a). Second, some facilities take putrescent and liquid material directly to already maturing piles for immediate incorporation and potential control in covered piles. Last, some waste haulers that continually deliver non-preferred material, have had their contracts suspended, showing a growing willingness from composters to place stringent controls on their suppliers (Coker, 2012a).

Biofilter and gaseous treatment technology

Use of negative air buildings for the receiving of material, and from other pre-processing units and compost piles, requires use of gas treatment technologies. Varying technologies have been evaluated and used at commercial scale. These include stacks/dispersion enhancers, chemical scrubbers, incinerators, catalytic oxidizers, adsorption systems, odor pile diversion, and biofilters (Schlegelmilch et al., 2005; Pagans et al., 2007; Wu et al., 2011). Brief descriptions of these technical approaches are given in Table 2.2.

Table 2.2: Technical approaches to gas emission treatment

Approach	Description
Stack/Dispersion Enhancers	Dispersion of odorous gases are enhanced
Odor Pile Diversions	Odorous gases from composting pile are diverted to flow over finished compost
Chemical Scrubbers	Odorous compounds are absorbed into a liquid then extracted with chemicals
Incinerators	Odorous compounds within gases are burned
Catalytic Oxidizers	Odorous compounds are oxidized to CO_2 and water facilitated by catalyst
Adsorption Systems	Odorous compounds are attach on the surface of an inert medium when gases are passed over
Biofilters	Odorous compounds are absorbed by microorganisms which are attached on the surface of support media

Stacks/dispersion technologies do not treat the odors, but merely reduce the concentration and potential impact of odors to the community. The other technologies all sequester odorous compounds. Among these, odor pile diversions are less effective at removing odors, but are relatively low cost (Schlegelmilch et al., 2005). More efficient, effective, and expensive methods can all achieve roughly 80-99% removal of odorous compounds, depending upon number of stages, flow/recycle rates and scale (U.S. EPA, 1994). Among these high-performing methods, comparison becomes essentially one of capital and operating costs given that performance is similar. Ottengraf and Diks (1992) compared technologies and found that incineration had the highest capital and operating costs. Chemical absorption was comparable to biofiltration in capital costs but 2-7 times more costly from an operating perspective. Thus, the vast majority of US and international installations are utilizing biofilter approaches for odor treatment (U.S. EPA, 1994; Coker, 2012a).

Biofiltration uses packed beds of porous media or biofilters to capture and biologically treat organic odorous compounds from an air stream. Biofiltration can treat a variety of compounds simultaneously and is particularly suitable for the low concentration gas streams produced at compost facilities from the large airflow induced by operations. Chemical absorption systems using stacked towers and typically chemicals and water to absorb and neutralize odorous compounds can exhibit more predictable and consistent performance but are significantly more expensive to operate. They also use large amounts of water for the scrubbing process, thereby increasing the needed volume for liquid containment ponds.

Pagans et al. (2007) demonstrated that biofilters can remove considerable amounts of odorous compounds, including 94.7% of ammonia-N and 82% of VOC, when treating gas streams with low to moderate concentrations of ammonia. Unfortunately, as ammonia-N concentrations approached 2,000 ppm or higher, performance for both ammonia-N and VOC decreased precipitously—suggesting potential microbial inhibition from the free ammonia in the gas. This issue has been experienced commercially in Toronto, which had installed biofilters in an attempt to deal with odor concerns and temporary closure of some composting facilities resulting from increased flows of food scraps. They then experienced biofilter failures due to ammonia toxicity, and in response installed ammonia scrubbers prior to gas entry to biofilters (Gorrie, 2010). This example is emblematic of a growing commercial interest in staged systems that attempt to more adequately treat high flow rates and avoid inhibitory impacts to the biology/chemistry (Wu et al., 2011). Emphasizing this trend, Toronto has also chosen to construct dispersion towers to further dilute odorous compounds after staged biofiltration—showing a profound commitment to odor control within the municipality (Gorrie, 2010).

One result of increased food scrap composting is the need for increased aeration to manage moisture content and high oxygen demand of the quickly degrading material. An unfortunate consequence of increased aeration rates is decreased gas retention time within biofilters, often dropping below the minimum design requirement of 45 seconds and preferred retention time of 60-70 seconds (Coker, 2012a). The result is decreased performance or even failure of the biofilters. From an operation and maintenance perspective, the addition of biofilters to a composting system requires significant pre-engineering to ensure that piping is adequately sized and designed to meet the unique attributes of the compost facility. Operators must also be trained to provide normal inspection and maintenance of the biofilter during its planned lifetime of operation (Das, 2000).

Outside handling and pre-processing steps

Outside handling (defined as not within a controlled air building) is one of the most significant factors leading to odor impacts (Table 2.1). Enclosing as much of this processing within negative air buildings or structural covers as possible can assist with odor management either directly (containment, sequestration in biofilters) or indirectly (less moisture, greater operational control, etc., which can lead to less odor production). One outcome of this attempt is the installation of multiple biofilters to specifically treat air streams from sub-operations. Cedar Grove Composting (Seattle, WA) provides one example of this, with their planned control and routing of air streams from the grinding operation to a dedicated biofilter (Winges, 2011).

A particularly important method to reduce odors from outside operations is covering piles. Synthetic micro-pore or breathable fabric technology is expensive, but numerous studies show up to 80-90% reduction in total VOC, ammonia, and other odorous compounds compared to non-covered piles (Card and Schmidt, 2008; Card and Schmidt, 2012). Covers can assist in biofilter odor sequestration, depending upon aeration methodology and biofilter incorporation. They also control moisture and other compost parameters more efficiently, decreasing odor production. However, use of this technology does not completely prevent odor release, especially during building, preparation, and uncovering of piles (Winges, 2011; Bary et al., 2012).

In an attempt to reduce costs, active research and commercialization has occurred for biomass cap technologies (also called pseudo-filters). These technologies reduce odors by incorporating various materials at the top of the pile to adsorb and/or delay the release of odorous compounds. The top of the piles has been shown to be the source of 70-85% of emitted odors (Card and Schmidt, 2008). Research on biomass caps has shown as much as 75% reduction of total VOC and other odorous compounds during the first two weeks of compost treatment (note, the same study indicated that 70-80% of total compost VOC was released during the first two weeks) (Card and Schmidt, 2008). In this study, the biomass cap approach, which involved adding approximately 15 cm of unscreened, finished compost to the top of the piles, was by far the least expensive approach (Card and Schmidt, 2008). To further enhance effectiveness, these approaches can be combined with strategies discussed in subsequent chapters, such as biological and physical additives.

Recently built, modern facilities are moving toward sophisticated process control hardware and software to optimize the biological compost process, which can also improve biological control of odor. For example, aeration supplies biological oxygen needs, controls moisture levels, and moderates pile temperature. Thus, all three parameters are intimately linked. A simple approach is to simply set the aeration on a timer to adjust the aeration rate a few times, say at week two and week four during the primary process. However, biological degradation is not linear and is impacted greatly by the feedstock mix, which will change from pile to pile. Obviously this is not an optimal method for process control. A more advanced method of control is to monitor either temperature or oxygen concentration in real-time, using hardware/software to allow for feedback control on the aeration rate. For example, oxygen levels could be set at a low of 10% and a high of 18%, with aeration being turned down or increased, accordingly, via variable speed drives controlled by software which monitors sensors placed in the pile (Coker and Gibson, 2013).

Liquid storage tanks and ponds from leachate and storm water

Winges (2011) found that ponds and leachate storage are not a large source of odor. But, several BMP’s can be used to further reduce pond odor. The most effective method is to reduce or eliminate the volume of compost leachate produced. In high rainfall areas, covered structures reduce the volume of leachate, resulting in a more concentrated leachate that can be effectively managed by using it as makeup water for compost or alternatively aerating it. Rynk (1992) reported that the slab grade should be 1% (minimum), with 2-4% (preferred). Leachate puddles should be avoided as they generate odors and can delay leachate use or treatment (Coker, 2012a).

Product curing and storage

To decrease potential odors, finished product should be not be stored on-site for long periods. Some compost facilities have recently had trouble selling enough product to accomplish this, especially within urban zones with saturated compost markets. This issue can be exacerbated for some facilities composting food scraps, if inert contaminants (e.g. plastic ware) and incomplete composting lower product quality (Brinton, 2000; IWMB, 2009). A holistic approach that emphasizes effective pre-treatment and biological controls is needed. This can produce higher quality compost, which in turn should enhance marketing, improve throughput, and reduce odors (Brinton, 2000; IWMB, 2009).

Site footprint and setbacks

For new sites, it is suggested that (1) multiple alternative sites be considered, balancing in particular hauling distance and neighbors, (2) adequate setbacks be determined and used, (3) suitable soil, drainage, slope (2-4%; Rynk, 1992) and land area for planned flow rate be achieved, (4) varying design and treatment technologies be considered and evaluated by environmental engineers with respect to impacts on economics, compost quality and odor, and (5) dispersion modeling be conducted under worst-case scenarios with the same environmental engineering consultants (Giggey et al., 1995). Setbacks (an area of buffer land separating the compost facility from active population zones) are critical as no facility will remove all odors. The desired setback will depend on location and distance to neighbors, but practical experience dictates a minimum setback of 2,000-3,500 feet. Many facilities that fall below this range have received complaints or have shut down due to community pressure (Giggey et al., 1995).

Compost operations are for-profit businesses. As such, there is pressure to increase flow rate (to increase the tipping fees they receive). There is also pressure to reduce capital costs (land and/or permanent infrastructure needed) and operating costs (labor, equipment, electricity, etc.) (Pacificlean, 2013). Meanwhile, solid waste managers often encourage greater organics diversion, which can exceed facilities' capacity to compost (Gorrie, 2010). The result of overloading a facility will be discussed in detail in Chapter 3, focused on biological controls. In short, though, intensive loading puts inordinate pressure on the compost biology, requiring a firm understanding of the underlying biology and its reaction to pressures. It also requires a set of control mechanisms to manage the biology correctly for reduced odorous emissions and production of high quality compost.

Non-Anaerobic, Biological Approaches to Pile Management

Background

Prompted by the previously described interest in diversion of food scraps from landfills, particular attention has recently been placed on understanding the intricacies of composting material with significant amounts of highly biodegradable fresh grasses and/or food scraps (Beck-Friss et al., 1999; Chang et al., 2006; Richart and Walker, 2006; Eklind et al., 2007; Cheung et al., 2010; Sundberg et al., 2011; Sundberg et al, 2012). Feedstock that contains high proportions of highly biodegradable wastes places profound pressure on the biological process, requiring more stringent understanding and control.

Low pH and anaerobic conditions

Composting highly biodegradable material such as food scraps and fresh-cut green waste is highly prone to (1) acid pH and (2) shifts from aerobic to anaerobic conditions, particularly during the important, first stage of processing. Initial acid feedstock or immediate acidification of the compost severely inhibits aerobic organisms within compost piles (Sundberg and Jonsson, 2008; Kurola et al., 2010; Partanen et al., 2010). This results in abnormally low concentrations of *Bacillales* and Actinobacteria, groups of microbes known to be critical for effective composting, particularly during initial stages (Cheung et al., 2010). Acidification promotes communities of *Lactobacillus, Clostridia* and *Escherichia coli* bacteria (Sundberg et al, 2012; Partanen et al., 2010, Smars et al., 2002; Sundberg et al., 2004), organisms that are not typically found in stable composts. (Sundberg et al., 2012). These bacteria thrive under higher temperatures and more acid conditions. At more acid conditions (less than 6 pH) and higher temperatures (greater than 40°C) *Lactobacillus* and *Escherichia coli* bacteria can proliferate and produce acids. This results in further depression of the pH (greater acidity). A biological feedback loop then occurs which inhibits growth of beneficial microbes (Brinton, 1998; Smars et al., 2002; Sundberg and Jonsson, 2005; Cheung et al., 2010; Sundberg et al., 2011). The shifts in pH and microbial populations lead to the production of even more acids (acetic, propionic, butyric and lactic acids). These acids are known to be odor sources (Brinton, 1998). Until recently, organic acids have received relatively little attention in compost odor research, though their production has been observed in mushroom composting (Noble et al., 2001) and composting of food scraps (Gallego et al., 2012; Krzymien et al., 1999; Komilis et al., 2004; Mao et al., 2006; Tsai et al., 2008). These authors noted the acid concentrations, but did not comment on the implications to odor production.

Anaerobic microbial cultures have been documented at large compost operations with high flow rates and excessively large piles (Brinton, 1998; Reinhardt, 2002). As noted, food scraps and grass clippings degrade quickly and use up available oxygen in the compost pile, yielding an environment where anaerobic cultures can be even more profound. Under depleted oxygen conditions, the anaerobic cultures are also capable of producing acids, lowering the pH and reinforcing the shift in microbial population. Anaerobic processing also yields significantly greater levels of climate changing greenhouse gases (GHG) such as methane (CH_4) and nitrous oxide (N_2O) (Hellman, 1997). Beck-Friis et al. (1999) showed that mean CH_4 and N_2O fluxes for large commercial piles were 35 g CH_4/m^2 day and 0.261 g N_2O/m^2 day, respectively, 4x and 3x fluxes of small piles, respectively. Lastly, anaerobic conditions can result in inferior product quality that may not meet pathogen-related regulations. A sampling of 94 non-sludge commercial compost products by Brinton et al. (2009) showed that 20%, 28% and 47% of products sampled exceeded limits for *Clostridium perfringens*, *fecal Coliforms*, and *fecal Strepptococci*, respectively.

Impacts of the negative pH cycle

Without controls, the negative feedback loop can accelerate, resulting in an abnormally long first phase of composting, and extended time for final compost maturation. While the extended composting time does not necessarily yield greater mass releases of volatiles, it does stretch the release over a greater period of time. It may also lead to a potential for greater release of volatiles during scheduled periods of material transfer. For example, an operator may assume that at the end of the 30-40-day cycle, piles can be uncovered, transferred, and turned with minimal release of ammonia and odorous compounds. However, if the composting period is delayed due from inhibitions, then composting may not be complete. If the operator does not recognize the issue, increased amounts of odors may be released.

In part due to the chemical nature of food scraps but also because of difficulties in controlling biological inhibitions, food scrap compost releases nearly 65% of its nitrogen as ammonia, emitting 34-41 g N/dry kg (Ham and Komilis, 2003). This is about 20 times greater than other common compost feeds. Ammonia is released in much larger volumes than other carbon-based odorants, but these too can be released in larger volumes than would normally be expected from non-food scrap compost, yielding odorous products such as terpenes, alcohols, esters, organic-sulfur compounds, and ketones. Significant levels of dimethyl disulfides, dimethyl trisulfides and limonene have also been detected from food scrap compost (Ham and Komilis, 2003). Total volatile organic compound (VOC) emissions of 2.8 and 2.1 mg VOC/DW for food scraps and grasses have been reported, respectively (Ham and Komilis, 2003).

In addition to increasing the risk of odors, delays in the compost process affect facility economics and product stability. Extended composting time leads to more piles and a reduction in free surface area within the facility. This in turn either leads to less product flow-through (negatively impacting economics) or a need to compensate for longer times with larger piles (reducing product quality). Concurrently, compost facilities have been negatively impacted by poor sale prices for their compost products (Ham and Komilis, 2003). This economic situation only increases the pressure to maintain high flow rates (income through tipping fees) and a high ratio of food scraps (greater tipping fee value) through the use of larger piles, higher temperature, etc. Unfortunately this business approach can lead to, or enhance, the negative biological feedback loop and production of odorous compounds. It is thus imperative that a combination of economics, markets and regulatory oversight allow for development of appropriate business plans that accentuate biological controls for control of inhibitions and odor while also yielding suitable economics and quality compost for end-users.

Best management practices to manage the low pH negative cycle

Best management practices can help prevent the negative low pH cycle. Many of the BMPs are interrelated, with modifications to one parameter affecting multiple others.

- *Aeration:* During late composting, when highly biodegradable material has already been processed and microbial activity and demand is therefore significantly reduced, typical target aeration rates are on the order of 200-500 cubic feet per hour per dry ton compost being treated (cfh/dt). However, during the first phase with high microbial activity, aeration should be on the order of 2,000 cfh/dt. Food scraps and grass clippings require even greater aeration (Coker and Gibson, 2013). Aeration not only supplies oxygen for biological processing but also helps reduce moisture and control temperature. Coker and Gibson, 2013 note that food scrap compost commits 4.3%, 18.2%, and 77.5% of aeration inputs to biological decomposition, moisture control, and temperature control, respectively.
- *Oxygen Concentration:* It is suggested that pile oxygen concentrations never drop below 8-10%. During the primary composting stage 10-18% is ideal (de Bertoldi et al., 1988; Coker and Gibson, 2013). Food scrap composting should be closer to the 18% maximum during the first phase. Beyond meeting the needs of aerobic microbes, adequate oxygen reduces the tendency towards anaerobic micro-zones within the pile and its corresponding push toward low pH negative feedback cycles.
- *Moisture:* Compost guidance states that moisture levels within a pile not exceed 60% (Wilber and Murray, 1990), and more preferably be controlled at the lower end of a 50-55% range (Coker, 2012b). Moisture targets should be even lower and should be closely monitored with food scrap composting. This target can be difficult to achieve given the intracellular water in food scraps that will rapidly be released during composting hydrolysis (Oshins, 2006). Composting in wet climate areas or seasons makes this even more difficult. Preferred practices include covered structures and/or pile covers. Additional BMPs involve immediately laying received food scraps on absorbent biomass during storage in negative air buildings so that intercellular water can be removed prior to pile construction (Coker and Gibson, 2013). High aeration rates may also help with moisture control.
- *Temperature:* Pile temperatures should not exceed 65ºC (Epstein 1997; Insam and de Bertoldi, 2007). Food scrap and green grass clippings are highly energetic and release abundant heat during decomposition, thus requiring greater aeration to keep the temperature below maximum. Eklind et al. (2007) showed that temperatures greater than 67˚C lead to more than double the ammonia emissions as compared to temperatures of 40˚C and 55˚C. Eklind et al. (2007) and Diaz et al. (1993) also found that optimal degradation occurred at the more moderate 55˚C level. Temperatures in excess of 70˚C have been shown to significantly inhibit desirable composting. Sundberg et al. (2011) emphasize that lower temperature range composting during the first phase better controls acid production. This avoids conditions that can be preferred by *Lactobacillus* and *Escherichia coli* while also reducing the production of odor-causing acids and ammonia (Sundberg et al., 2012). Sundberg and Jonsson (2008) have even suggested a phased

temperature regime—an initial phase not to exceed 35°C appreciably delaying the higher temperatures suggested during a thermophilic stage.

- *Process Controls:* Modern, real-time process controls were previously mentioned as important tools to maintain optimal compost biology. It can now be seen that aggressive on-line monitoring for pH, acids, oxygen levels, and temperature may be necessary, with automatic adjustments in aeration or other management strategies. It is broadly accepted that aerated static pile composting is more fastidious and prone to upset than windrow composting (Coker and Gibson, 2013). The combination of aerated static piles and high ratios of food scraps and other putrescent organics is thus doubly difficult, requiring large compost facilities to move towards greater process control via modern probes/software.
- *Pile size:* Piles should not exceed 10 feet in height with an approximate width of 25 feet (Winges, 2011; Beck-Friis et al., 1999). Larger piles significantly increase the risk of producing anaerobic environments. They also generally result in a higher thermophilic operating temperature, which can be as high as 80-90ºC within many facilities, particularly those utilizing active covers (Richart and Walker, 2006), unless active temperature control via aeration is practiced.
- *Nutrients and C/N ratio:* The preferred feed to the compost pile has a C/N ratio between 20-25 and a carbon content that is not too low or high in non-biodegradable lignin (IWMB, 2007). The incorporation of roughly 10-15% of recycled finished compost as seed (Coker and Gibson, 2013; Grey et al., 1971) is preferred because of the multiple benefits it provides: added moisture absorbance, concentration of preferred biological consortiums, and some added level of odor control due to physical/chemical absorption.
- *Bulk Density/Porosity*: Particle size should not be smaller than 2-3 inches (Coker, 2012b) in order to maintain effective air capacity within the pile (Coker, 2012b). Extensive blending of food scraps will be needed because food scraps will readily collapse in size while also tying up the air capacity with bulk water. An emerging trend in compost management is to more often test for air holding capacity as a key parameter. The goal is to ensure that across the pile values stay within the range of 40-60% (Coker and Gibson, 2013).

Many of these BMPs may add considerably to both capital and operating cost while also increasing operator complexity. Such cost implications could undoubtedly affect project economics and be in direct conflict with compost facility preferences to reduce costs in the face of continuing challenges relating to compost sales and operation.

Summary of best management practices for low pH

Table 3.1 summarizes BMP parameters for large-scale digestion of significant fraction of food scraps and/or putrescent material within a wet climate.

Table 3.1: Suggested BMP parameters

BMP Parameters	Operation
Plan/Footprint	Size to handle flow rate; 2,000-3,500 ft^3 set back; 2-4% slope
Structures	Large tipping building, covered structures, biofilters
Composting Type	Micro-pore covers; aerated static pile
Process Controls	Complex, real-time monitoring many parameters & feedback
Aeration	Variable drive, phased 2,000+ to 200-500 cfh/dt
Oxygen Content	> 10-18%, but preferred on high end
Moisture	< 60%, more between 50-55%, pre-controls on food scraps
Temperature	Variable drive, phased 35ºC then 50-55ºC, no > 65ºC
Pile Size	No greater than 25’ by 10’ (width x height)
Mix/Nutrients/C-N Ratio	C/N 20-25; optimal Biodegradable C; 10-15% seed rate
Bulk Density/Porosity	2-3” particles; > 1,000 lb/yd^3 bulk; 40-60% air capacity

Effective microorganism seeding

Other biological approaches to odor management and high quality compost production do exist. An active area of both research and commercial application is use of effective microorganisms (EMs) for enhanced composting. EMs are specifically cultivated and designed inoculums of microorganisms and/or enzymes considered beneficial to biological treatment (Goldstein, 1994; Bundy and Hoff, 1998; Das, 2000).

One important example of EM is the Bokashi Composting System (BCS) (Pontin et al., 2002; Yamada and Xu, 2000). In BCS, specialized EM cultures (> 80 species; Powell, 2013), composed of lactobacilli, purple non-sulfur bacteria, yeasts, and actinomycetes that are fixed to bran/sawdust media for inoculation to piles, are introduced to accentuate the natural compost operation. An evaluation of the properties of these organisms indicates that the BCS might be particularly adept at composting highly biodegradable material. Many of these species are tolerant of both aerobic and anaerobic conditions as well as tolerant to low pH environments. They are also capable of metabolizing energy-rich substrates such as carbohydrates (Daly and Stewart, 1999).

Two products are outcomes of EM, a liquid rich in acids, and a fermented solid somewhat like silage or kimchi. The liquid results from a higher ratio of fermenters, particularly lactobacilli (Barnes, 2009). Interestingly, higher chain organic acids can have unique, and often times pungent odor. Thus, a question arises as to suitability of this process at large-scale facilities already experiencing odor concerns, as in this process altered but still potentially pungent odors will be produced, with specific odor qualities and odor tests needed to determine final consumer satisfaction (Sundberg et al, 2012). The solid product is a result of the enriched aerobic/anaerobic (also called facultative) microbe populations that remain fixed to the solids. Some studies of BCS show a positive impact on plant growth from this solid product while others show no benefit (Mayer et al., 2010). Thus, while potentially useful as an advanced inoculum well suited for food scraps and grass clippings, a question remains with the value and use of the co-products (Powell, 2013). BCS and other EM methods are similar to other biological decomposition that use fungi or worms to treat waste for production of a soil amendment while also producing valued co-products, as in the case of mushroom farming and/or vermicompost (Noble et al., 2001).

Vermicomposting

Vermicomposting is an important organic waste management method resulting in value-added co-products. Vermicomposting is a proven aerobic treatment used to treat sewage sludge, brewery waste, paper waste, urban residues including food scraps, animal wastes, and horticultural residues. It is similar to bacterial/fungal compost. Earthworms consume the bacterial/fungal microorganisms and products of decomposition (Dominguez and Edwards, 2004). Like composting, the process is sequential, undergoing various stages of hydrolysis/fragmentation, biological aerobic oxidation, and final product carbon stabilization. Similarly, the process is carried out by groups of microbes resulting in numerous interactions between microorganisms, earthworms and soil invertebrates (Dominguez and Edwards, 2004). The process is best described as being driven by microbes and accentuated by earthworm. That is, the microorganisms do the actual conditioning and treatment while the earthworms facilitate in specific ways, by reducing particle size, increasing air capacity, enhancing surface and air properties, facilitating macro/micro-aeration, and mixing the waste while making it more consistent. This is a result of worms eating, moving, metabolizing, and defecating. The organic waste is carbon stabilized and the co-product worm castings can be sold as a sought-after soil conditioner (Wang et al., 2009). In addition, a net supply of worms can result, generating extra market income.

Conclusion

As more compost facilities are asked to process increasing flow rates containing higher percentages of highly biodegradable food scraps and grass clippings, greater process control will be required to mitigate odors and produce quality compost. These process controls are summarized in Table 3.1. It is important to note that many of the suggestions require increased capital and operating investments, and increase complexity and the need for worker skill/knowledge. Regulatory agencies will undoubtedly play a role as they grapple with continued occurrences of odors, with roles potentially including enhanced design criteria, regular reporting of on-line monitoring with feedback control, and establishment of maximum flow rates and processing times. Control of biological operation through tweaking of systems and operations that dictate biology and chemistry are not the only mechanisms available, with other mechanisms including the aforementioned EM methodologies and use of physical/chemical additives to be discussed in the next chapter. For some moderate to smaller size operations, high-value treatment, be it BCS, mushroom, or vermiculture, has been a successful strategy.

Anaerobic Approaches to Treatment of the Highly Biodegradable Fraction of Municipal Solid Waste

Background

Another strategy to address concerns experienced during the compost treatment of food scraps and/or green waste is adding a preliminary anaerobic digestion (AD) step. This strategy allows highly biodegradable material to enter an acidic odor-producing feedback loop, and permits the tendency towards anaerobic processing (Sundberg and Jonsson, 2008; Kurola et al., 2010; Partanen et al., 2010). This is in contrary to other strategies, which work extensively to monitor/control process conditions so that aerobic conditions are maintained (de Bertoldi et al., 1988; Coker and Gibson, 2013). In a dedicated AD system, runaway decomposition is managed in a controlled anaerobic enclosure, which provides the opportunity to control odor releases, while also producing renewable energy and recovering nutrients. It is notable that this process generates renewable CH_4 gas from the energy within the food and green waste, whereas control of the compost operation requires energy inputs for aeration.

AD is not a panacea, as it can also be upset by high biodegradability, low pH, and high nitrogen levels present in food scraps and green waste. AD is a process of sequential but synergetic biological steps (Figure 4.1). Decomposition of the waste occurs through steps that first break down large complex molecules into smaller molecules and then converts these into small acid molecules such as acetic acid. Small acid molecules are use during the final CH_4-formation step. These processes must be managed so that the digester operates consistently. Otherwise the process can become inhibited, soured or even fail (Mata-Alvarez et al., 2000).

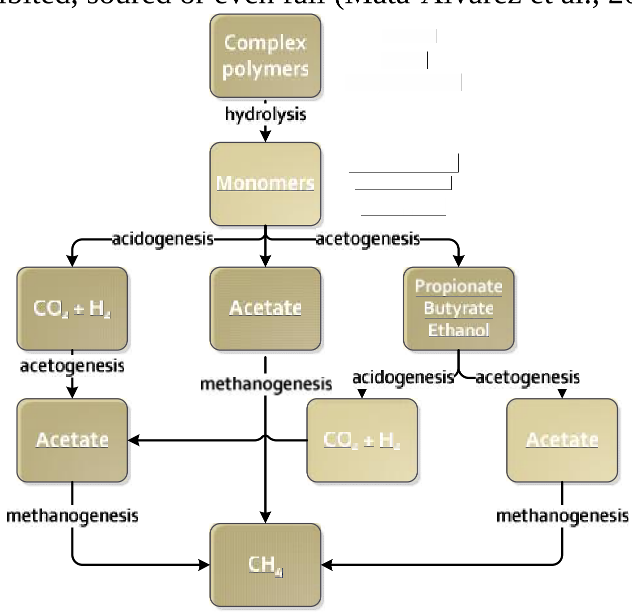


Figure 4.1: Anaerobic digestion process (Britton, 1994)

An additional concern is the high capital and operating costs that have been associated with AD units primarily treating the organic fraction of MSW, as they have developed over the last decade in Europe (Figure 4.2). Figure 4.2 indicates that a typical 100,000 metric ton (MT) plant would have capital costs around \$15-20 million with operating costs at \$80-100/MT treated. While these costs might be economically viable for projects capable of receiving 20-30¢/kWh for the energy they produce, they represent unreasonably long project paybacks within the US, given typical electrical sales prices of 4¢/kWh.

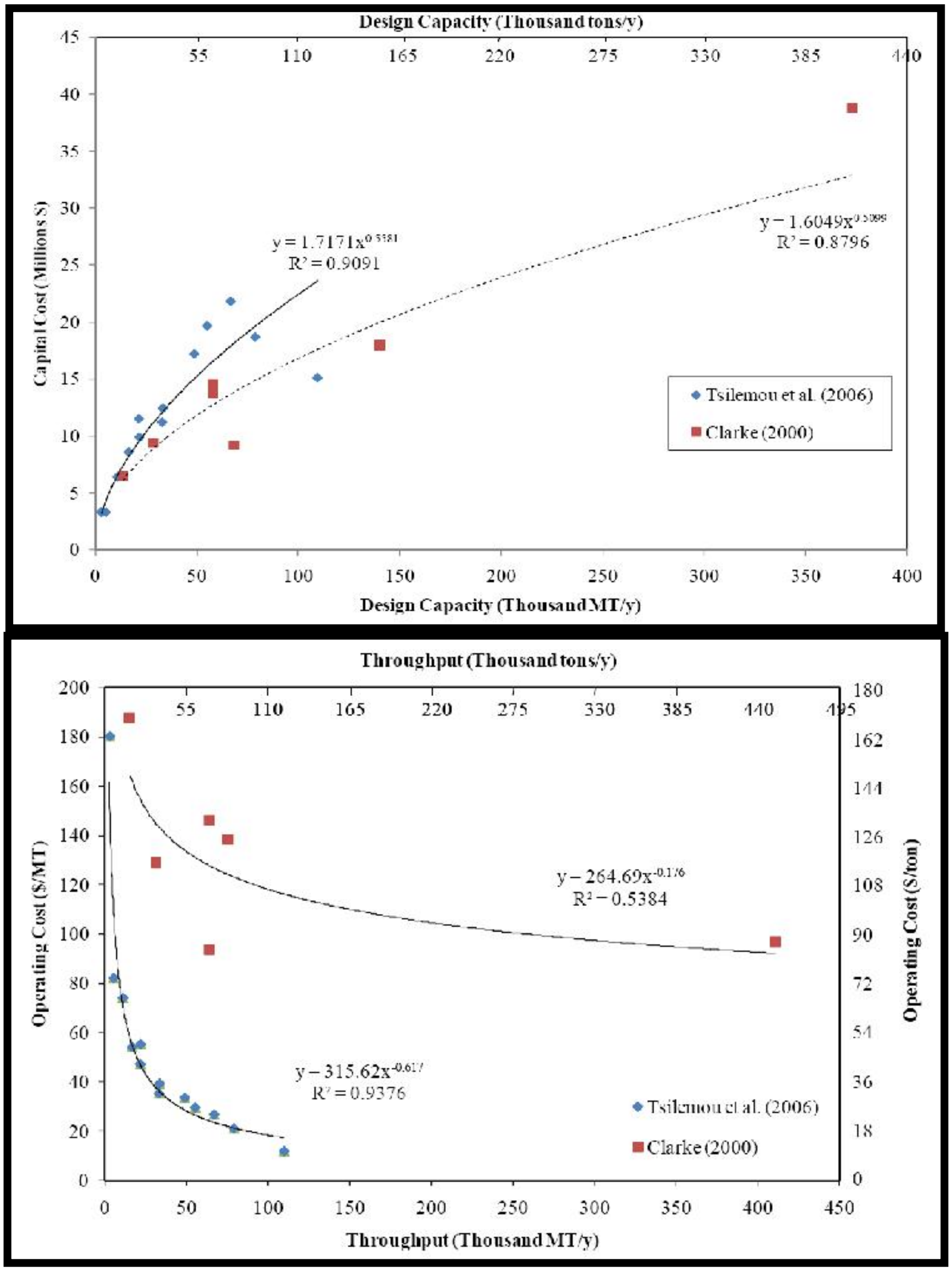


Figure 4.2: Capital cost by design capacity and operating costs by flow throughput for commercial digesters for the organic fraction of MSW as reported in Hartmann and Ahring, 2006a

For AD to be applied to food scraps and green waste in the US, project economics will need to be improved. If food scrap and green waste digesters follow the same adoption path as US farm-based, manure digesters, viable economics will eventually result from a combination of (1) less costly operations, if not also capital construction; (2) multiple product revenue streams; and (3) technologies and product streams being able to resolve regulatory concerns (i.e. GHG emissions, overloading of nutrients to soils, etc.) while producing renewable energy (Frear et al., 2011; Bishop and Shumway, 2009).

The literature is laden with descriptive phrases for various digestion technologies used in AD. These include wet digestion, dry digestion, high solids anaerobic digestion (HSAD), and others. Food scraps and green grass waste are drier (higher in solids concentration, 15-35% total solids (TS)) than municipal wastewater and manure feedstocks used more commonly (2-10% TS). However, the many descriptors may contribute to misunderstandings. During actual digestion of food scraps and grass waste, the initial feedstocks may be diluted in various ways and thus might not be particularly "dry" or "high solids".

Figure 4.3 outlines the major types of AD technologies, using new terminology to more directly describe the processing technologies and reduce the potential for misunderstanding. Each of the approaches can be operated at either mesophilic or thermophilic temperature regimes. Temperature regime will only be briefly discussed here. Some literature has shown evidence that thermophilic temperatures enhance overall efficiency, volumetric productivity, and even specific methane productivity with minimal concerns related to operational stability (Hartmann and Ahring, 2006b). Other researchers have lingering questions regarding some aspects of operational stability (Mata-Alvarez, 2000).

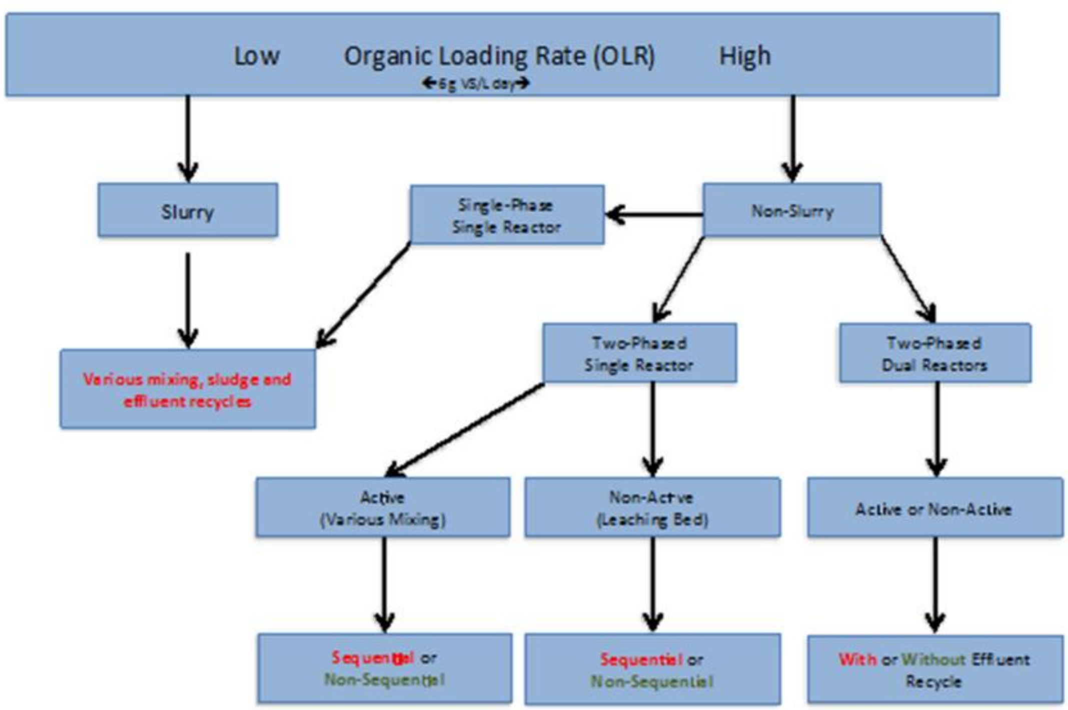


Figure 4.3: Summary of various MSW organic AD technology approaches

Figure 4.3 separates technology into slurry-based and non-slurry based approaches. Slurry-based approaches actively dilute the waste stream with liquid so as to attain a lower TS level suitable for active mixing. This allows for process homogeneity and presumably enhances efficiency, microbial populations, and microbial/waste interactions. Liquid dilution can occur through any combination of water addition, return-water recycle and/or co-digestion. The latter two use less water and generally improve the ability to attain desirable nutrient and organic levels, buffering control and/or reduce process system costs. Typical slurry systems include common municipal and manure fed systems such as complete mix and/or plug-flow or combinations thereof. However, at higher organic loading rates (identified as rates above 6 g VS/L day by Hartmann and Ahring, 2006b), non-slurry digesters begin to out-perform slurry digester in terms of several metrics. This is presumably because homogeneous mixing and enhanced degradation result in rapid product inhibition that cannot be controlled, leading to either depressed performance or complete failure of the digester.

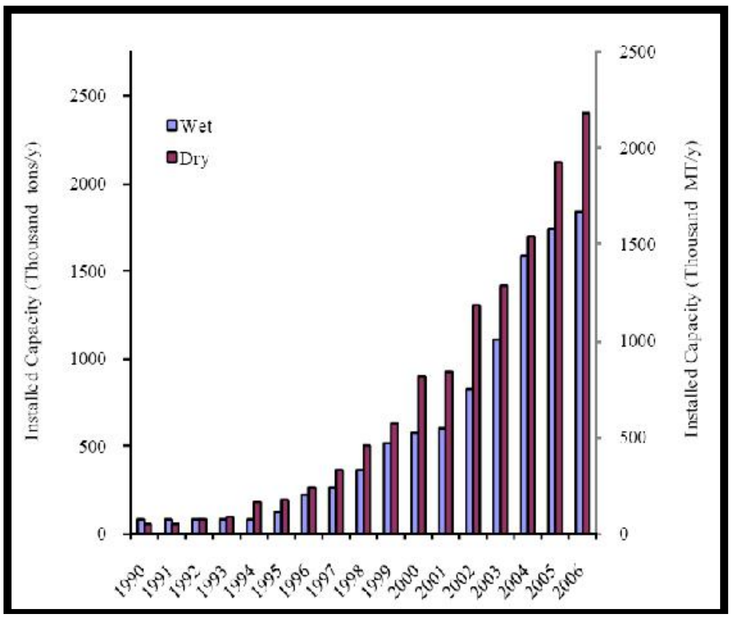


Figure 4.4: Trends in slurry (wet) and non-slurry (dry) AD of the organic fraction of MSW (Hartmann and Ahring, 2006a)

In contrast, non-slurry approaches do not actively dilute the solids, but instead maintain a bed of solids or a thick paste. This bed or paste is either not actively mixed or, if mixed, is mixed primarily for material transfer rather than for homogeneity. Considerable amounts of liquid can still be utilized by some of these systems. During early years of digestion of the organic fraction of MSW, slurry systems predominated, presumably because of familiarity with common complex mix designs. However, there has recently been more rapid adoption of non-slurry systems, resulting in a sharing of market percentage between the two types (Figure 4.4). Bolzonella et al. (2006) state the benefits of reduced reactor volume and wastewater production as primary reasons for increased market adoption of non-slurry systems, although Hartmann and Ahring (2006a) point to concerns with material handling which at times might limit adoption.

Existing and on-going projects within the United States and Canada

In Oakland California, the East Bay Municipal Utility District's (EBMUD) digester converts post-consumer food scraps from local restaurants to energy via AD (Figure 4.5). The EBMUD study found that the CH_4 production potential of typical municipal biosolids was 120 m^3 gas/ton compared to food scraps at around 367 m^3 gas/ton. Additionally, they found that anaerobically digesting 100 tons of food scraps per day, five days a week provided sufficient power for approximately 1,000 homes.

(a)

(b)

Figure 4.5: Exiting anaerobic digesters at: a) EBMUD Wastewater Treatment Plant in Oakland, California, b) Chino, California

Starting in October 2006, about eight tons of food scraps per week from San Francisco restaurants were processed through the Biogas Energy Project at the University of California. The system has been expanded and can handle almost 60 tons of waste per day, while its series of digester tanks can treat 8 tons of solid waste per day—which in turn produces enough biogas to power 80 homes (Zhang et al., 2008).

In Chino, California, two continuously stirred digesters treat 350 tons of food scraps daily (Figure 4.5; McNamara and Eowan, 2012). In December of 2012, the California Energy Commission awarded this operation $2.6M to upgrade the biogas into compressed natural gas (CNG), construct fuel stations and purchase alternative-fuel vehicles. At full operation, the facility will create 750 to 1000 – diesel gallons equivalent of CNG for the collection trucks, providing a complete circle from waste collection and disposal to biofuel production and utilization. After the digestion process, the leftover material can be composted and used as a natural fertilizer.

The first dry fermentation anaerobic digester in the Americas was built at University of Wisconsin Oshkosh. The unit treats about 8,000 tons of food scraps and green waste per year, and converts it into biogas for electricity and heat. It is designed to produce an average of 2,320,000 kWh annually, providing 8% of the University’s electricity needs on its campus.

Additionally, the plant will generate 7,900 MMBTU of thermal energy to heat adjacent campus buildings.

The City of Toronto's Dufferin Organics Processing Facility has a capacity of 25,000 MT per year using wet digestion. Toronto's Green Bin program provides curbside household organics collection to 500,000 households and 20,000 businesses. The combined businesses and households provide a large source separated organics stream to the facility. Since this plant was primarily designed as a demonstration plant, it does not have an energy conversion system and all biogas is combusted in an open flare. The Dufferin station will be shut down in 2013 so it can be doubled in size to 50,000 MT of annual capacity.

In Richmond, British Columbia, Canada, an HSAD was just completed to process 50,000 tons of food scraps and green waste annually. The digester is expected to reduce GHG emissions by about 9,000 MT of carbon dioxide equivalents (CO_2e) each year and produce 2 MW of energy; enough to power more than 900 lower mainland homes.

Benefits of combining anaerobic digestion and composting

There can be significant benefits from composting after AD treatment. A 2001 study comparing a combined AD and compost operation to composting-alone showed a sevenfold decrease in releases of ammonia and VOC from the combined system (Mata-Alvarez et al., 2000). A Swedish study found that the lowest GHG emissions resulted from combined digestion and composting relative to composting alone or landfilling (Bernstad and Jansen, 2011). Unfortunately, there are still obstacles to achieving this powerful integration of AD and composting in commercial organic recycling facilities in the US. Financing a project is one substantial challenge. Therefore, no combined systems have yet been installed in an organics facility in the US.

Compost facilities are capital and operating cost intensive, but adding commercially available AD systems to process food scraps can double these costs. For perspective, a typical 150-250 MT/day AD unit appropriately sized for West Coast cities will cost roughly $15-20 million to construct and around $0.5M annually to operate (Hartmann and Ahring, 2006a). The economics strongly depend on the organic waste characteristics, electricity costs and solids residual costs (Parry, 2013). To make the system work, the required tipping fees for food scraps vary from 0 to $170/dry ton for electricity costs of $0.05 to 0.20/kWh. European digesters have been economically viable due to much higher electrical power rates than are generally available in Western North America.

There are also processing challenges that need to be overcome for successful commercial digestion of energy-rich food scraps. While food scraps are more readily degradable than manures and wastewater (traditional digestion feedstocks), they are also much less stable in the digestion process (Shin et al., 2001; Ewing and Frear, 2012; Han et al., 2012). Therefore, process control mechanisms must be built into the digestion technology to create a stable process for CH_4 production. Contaminants (i.e. plastics, garbage) in food scraps create an additional processing concern for commercially available digesters, as non-organic contaminants can clog the digester and cause mechanical failures in moving parts within the sealed container (Bernstad and Jansen, 2012; Sullivan, 2012). While experience has shown that each of these problems can be addressed in a commercial setting, they do add to the capital and operating costs and therefore the economic burden.

The final challenge that must be overcome is the water balance within the digester. Food scraps are approximately thirty percent solids but traditional slurry-based digestion technology requires material of less than ten percent solids. Concerns about water use thereby argue for high solid designs instead of slurry-based designs, unless ways to reduce fresh water input are overcome via active return-water recycle. Unfortunately, existing inhibitors within the post-digestion liquid preclude its recycle unless nutrient recovery and other cleaning technologies are incorporated into the overall system. This inclusion would add complexity and cost, which might not be offset by any co-products that could be sold (Zhao et al., 2011).

An emerging opportunity that may improve overall economics is the utilization of biogas for production of CNG, instead of the typical production of renewable power. Production of CNG is a good option for a site where the electric power price is low (Coppedge et al., 2012). Consistent production of CNG provides a low-cost and renewable fuel for the waste collection fleet, which could be perfectly tied into the compost facility operation (Chino, CA).

The comparison between stand-alone aerobic composting and the combination of AD plus composting is complex. On the one hand, it appears that a combined AD-compost system can recover a variable amount of energy, whereas composting is a net energy consumer. However, it is also true that anaerobic technology requires larger investment and adds considerable complexity. Many comparisons have been carried out in the past, but with different results, many of which depended on energy costs. However, Edelmann et al. (1999) compared, in both ecological and economical terms, different processes for treating biogenic wastes in facilities with a treatment capacity of 10,000 tons/yr of organic wastes. After a series of measurements at compost yards they found that the CH_4 emissions were greater than they had assumed. Life Cycle Analysis showed that stand-alone AD was more advantageous than composting, incineration or combination of digestion and composting, mainly because of its improved energy balance. They concluded that anaerobic processes will become much more important in the future for ecological reasons.

AD should be considered in the context of an overall sustainable waste-management strategy. Aerobic treatment produces large and uncontrolled emissions of volatile compounds, such as ketones, aldehydes, ammonia and CH_4. Table 4.1, extracted from De Baere (1999), shows the different emissions of volatile compounds during aerobic composting as compared to combined AD plus composting.

Table 4.1: Emissions of volatile compounds during aerobic composting and during maturation after anaerobic digestion (De Baere, 1999)

Compounds	Aerobic g/ton	Post Anaerobic g/ton	Ratio Aerobic/Anaerobic
Alcohols	283.6	0.033	8,594
Ketones	150.4	0.466	322
Terpenes	82.4	2.2	37
Esters	52.7	0.003	17,567
Organic Acids	9.3	0.202	46
Aldehydes	7.5	0.086	87.2
Ethers	2.6	0.027	96.3
Total VOC	588.5	3.02	195
Total Ammonia	158.9	97.6	1.6
Total	747.4	100.6	7.4

A consideration not mentioned by Edelmann et al. (1999) is that while the AD alone scenario proved more effective under their LCA conditions, not all diverted organics are well suited for AD treatment. Woody material with a high lignocellulosic content is more effectively processed through composting. Thus, the fusion of compost and may allow for flexibility in treating a range of biomass types. Kubler and Rumphorst (1999) reported that a 25-67% reduction in carbon dioxide (CO_2) emission (depending on the use of the exhaust heat) was achieved in a combined plant using AD and aerobic post-composting. In addition, a composting plant treating 15,000 tons/yr consumes about 0.75 million kWh/yr of electricity, whereas for AD the net production is about 2.4 million kWh/yr. The total produced electrical energy exceeds the amount of energy used for construction and operation.

Conclusion

A small but clear body of literature indicates the potential economic and environmental savings that could result from combined anaerobic and aerobic treatment of food scraps and green waste. Integrating AD can enhance organic recycling processing quality and performance, reduce odor, improve air quality, and reduce GHG emissions (Kubler and Rumphorst, 1999). Concerns remain, though, in regard to processing hurdles, added complexity to facilities, and most importantly project economics resulting from low received electricity prices in the US (Ewing and Frear, 2012). Further research is underway which could lead to breakthroughs in AD technology. The most important of these will reduce process cost and improve performance. Additional development of auxiliary technology, such as biogas conditioning and compression technology for generation of CNG for waste management fleets, may create a tipping point that encourages organics recycling facilities to pursue AD as a key strategy for processing food scraps.

Use of Amendment Approaches to Pile Chemistry and Biology

Background

This chapter examines the odor-control potential of various charcoal-based materials – biochar, activated carbon (AC) and high carbon wood ash. This chapter will use the term biochar to refer to an un-activated charcoal that could be made from wood, bamboo, rice hull, grasses or other biomass. Wood ash, if it contains less than 10% carbon could not be termed biochar, so we retain the term "wood ash" even though wood ash materials termed "high carbon wood ash" generally contain more than 10% carbon and therefore could qualify as biochar. Several different industrial processes can produce AC, including steam or chemical washes that expand the surface area of the material and oxidize surfaces for greater reactivity. In general, AC is viewed as being effective but too expensive for widespread use in compost odor control. Indeed, the reason for considering high carbon wood ash as a compost admixture for odor control is largely because it is a waste product from biomass energy combustion that is obtainable at low cost. Biochar, on the other hand, is expected to have costs somewhere between wood ash and AC.

Biochar manufacturing converts easily degradable biomass carbon to stable charcoal. When incorporated into soil, it lasts for thousands of years in soil where it provides longstanding crop growth benefits (please see extended historical discussion in Appendix A). This process of stabilizing the biomass carbon into recalcitrant forms removes carbon from the rapidly cycling biogenic carbon pool, effectively sequestering it from the atmosphere for centuries to millennia. Biochar itself has very little in the way of plant nutrients; it functions rather as a matrix to hold nutrients and water that are plant available. Currently, researchers in the field are looking closely at ways to charge or engineer biochar with nutrients and beneficial soil microbes. Composting with biochar is emerging as a synergistic approach to improve the quality of both the biochar and the compost, with the added benefit of odor control in the composting process. Notable biochar composting programs are ongoing in Japan, Vietnam, India and various European countries.

The structural characteristics of biochar may provide benefits when it is incorporated into composting as a bulking agent or additives in compost, or if used for biofilters. As a bulking agent, biochar could have several advantages over more common bulking materials like straw or wood shavings. One function of a bulking agent is a structural support to create air voids between compost particles. As the compost ages, the bulking agent will degrade and have a tendency to collapse and increase in density—thereby reducing aeration. Using larger sizes of wood chips can prevent this, but precisely because larger wood fractions will not decompose completely, they may need to be screened out of the compost. Including a fraction of biochar in compost could prevent compaction of the compost throughout processing without the need for screening. As a biofilter, biochar could also perform well compared to woody materials that are often currently used. Over time, even larger woody material does break down and the biofilter compacts and loses effectiveness. Biochar could extend the life of compost biofilters by providing a stable carbon fraction to provide void space and that also supports aerobic compost microorganisms.

Aside from having significant stable carbon content, the other properties of charcoal materials can vary widely. Depending on the properties, the materials have different kinds of impacts on and interactions with the physical, chemical and biological constituents of both aerobic and anaerobic composts. Some important parameters include the mineral constituents (ash), the labile organic matter (non-stable carbon compounds), pH, electrical conductivity and the surface area or porosity of the stable carbon fraction. Surface area characteristics also vary and affect the sorption (absorption and adsorption) properties of biochar.

This chapter reviews recent scientific literature on the impact of charcoal materials on compost odor focusing on the three most important categories of odor for food scraps: sulfur-based, nitrogen-based and VFA odors. Among these categories, some of the most problematic odors from food scraps come from VFAs. VFAs arise primarily from the anaerobic decomposition of carbohydrates and lipids. Ammonia and hydrogen sulfide emissions are of secondary importance, but also result in nutrient losses that reduce the value of the finished compost. The mechanisms of odor control vary and may be physically, chemically or biologically based or a combination thereof. It also examines the impact of charcoal materials on GHG emissions from compost.

This chapter also examines how charcoal materials impact compost physicochemical and biological processes. When used as bulking agents, charcoal materials can impact pH, aeration, moisture content, temperature, bulk density, pile volume and surface area, absorptivity and adsorptivity of bulking agents, and the performance of covers and biofilters (IWMB, 2007). Changes in these parameters can in turn affect the proliferation and composition of microbial communities and the quality of the finished compost.

Volatile fatty acids

As mentioned above, some of the most problematic odors from food scraps come from VFA. Food scraps begin decomposing the moment they are generated. Collection bins are mostly anaerobic, so food scraps arrive at composting facilities with low pH and rapidly multiplying anaerobic bacteria. Sundberg et al. (2012) sampled compost odors and found that organic acids generated by anaerobes such as lactobacillus and clostridia were the primary sources of odor from food scrap compost. They proposed using rapid aeration, wood ash or lime and inoculation with finished compost to overcome acidity and control odor. Kurola et al. (2011) performed both pilot scale and large scale trials of wood ash in biowaste composting in Finland that included food scraps. Using up to 8% weight to volume of wood ash in the compost, they found that the ash raised the pH, accelerated the onset of thermophilic conditions, reduced acetic acid and suppressed lactic acid bacteria. However, the ash addition also increased emissions of CH_4, ammonia and sulfides. The authors did not report on the carbon content of the ash. They also found that the quality of the finished compost was slightly compromised by the addition of ash. The C:N ratio and the pH both exceeded compost standards in Finland. The authors speculate that nitrogen was lost due to ammonia volatilization, and cautioned that these results may indicate that ash compost should not be used directly as a plant growth medium.

Another approach using charcoal materials for controlling VFAs generated by food scraps has been to use biochar as a carrier of preferred composting microorganisms. Yoshizawa et al. (2005) used a microbial culture of aerobic complex microorganisms (ACM) seeded onto a mixture of sterilized rice bran and three different charcoals made from bamboo, wood waste and corn cobs. Observations with a scanning election microscope confirmed that the ACM proliferated on the surfaces of the biochars. They also measured adenosine triphosphate (ATP) as an indicator of the microbial proliferation and found that the control, with rice bran only and no biochar, did not sustain the culture. When added to food scraps, the system without biochar became acidic and produced VFAs and sour smells, even though all incubations were stirred to add oxygen once a day. Based on an examination of pore size distribution, the authors concluded that the three biochars were providing oxygen in pore spaces, effectively aerating the system and sustaining the ACM. Yoshizawa et al. (2005) then used these results to design a demonstration program for food scrap composting involving 50 households (Suwa City, Nagano Prefecture, Japan). Collected food scraps were mixed with charcoal, rice husk and ACM and then heated to 55 °C under aeration for 3 hours to kill the anaerobic organisms. Thereafter they composted in a mesh box for up to two months.

Currie and Briones (2012) found that biochar added to anaerobic food scrap composters resulted in large decreases in VFA production and detectable odors throughout the 93-day trial. Further work will characterize the changes in the microbial community in the different treatments. Biochar is also being examined for anaerobic composting of human waste. Factura et al. (2010) collected human fecal matter in airtight buckets over several weeks, adding a mix of biochar, lime and soil after each deposit of fecal matter. Two inoculants were tested - sauerkraut juice and EM, a collection of several species of bacteria, yeasts and fungi. The investigators found that the combination of charcoal and inoculant was very effective in suppressing odors and stabilizing the material.

High carbon wood ash is another material that has been examined. Rosenfeld et al. (2002) performed a pilot study on the feasibility of using high carbon wood ash to control composting odor emissions at a green waste composting facility in California. Using a wood ash with 15.6% carbon, they added 12.5% and 25% wood ash by volume to composting windrows. Compared with the control, both the 12.5% and 25% wood ash additions reduced emissions of VFAs and some aldehydes and ketones, with the 25% treatment providing better control over a longer period. In contrast, ammonia emissions increased in both wood ash treatments throughout the seven-day trial. The authors attribute this result to the strongly alkaline pH (10.3) of the wood ash at the time of addition. They also speculated that rinsing the wood ash to lower its pH could enhance control of ammonia emissions.

Ammonia and nitrogen-based odors

Activated carbon is effective in adsorbing ammonia (Rodrigues et al., 2007), and several researchers have looked at different forms of activated charcoal and wood charcoal for this purpose. Tamon and Okazako (1996) found oxidizing AC to create acid surface oxides greatly improved its ability to adsorb ammonia. Tsutomu et al. (2004) compared AC to wood charcoal as a sorbent for a number of gases and found that for ammonia, the wood charcoal outperformed the AC, even though it had less total surface area and pore volume. The process of sorption has different mechanisms, and can be impacted by operating temperature, pore volume and size, available surface area and chemistry of the surface area. In the study by Tsutomu et al. (2004), they found that the wood charcoal, because it is made at lower temperature than the AC, had retained acidic functional groups that reacted with the alkaline NH_3- gas. They also found that wood charcoal was a better adsorbent for methyl-amine, another nitrogen based odorous compost gas, but that AC performed better at adsorbing di- and tri-methylamine, due to the larger size of those molecules and the greater pore volume capacity of the AC.

Numerous studies have shown that biochar is effective at retaining nitrogen in soils (Steiner et al., 2008; Spokas et al., 2012; Clough et al., 2013). Several studies have also shown that biochar enhances nitrogen retention in compost, reducing ammonia emissions. Hua et al. (2009) added 9% bamboo charcoal to sewage sludge compost and found that the total nitrogen loss for the full composting process was reduced by 64.1% compared to no biochar. This was due to sorption of ammonium by biochar. Interestingly, they also found that composting had increased the capacity of the biochar to adsorb ammonium, more than doubling the amount of carboxylic (acid) functional groups on the aged biochar. In experiments with pine biochar and poultry litter, Steiner et al. (2010) observed a 64% increase in total nitrogen retention when 20% pine biochar was added, as compared to no biochar added. Chen et al. (2010) found that adding 9% bamboo biochar to pig manure compost reduced total nitrogen loss by 65% as compared to the control. Dias et al. (2010) found that N losses when using biochar made from eucalyptus in a 1:1 mixture as a bulking agent with poultry manure were lower than an equivalent ratio of coffee husks, but greater than when sawdust was used as a bulking agent. They concluded that the high pH of both the poultry manure and the biochar inhibited ammonia adsorption by the biochar. The pH and liming capacity of biochar materials can be highly variable, depending on feedstocks and processing parameters. These results show promise for use of biochar in controlling ammonia emissions, but they also indicate the importance of other factors such as pH, C:N ratio and biochar surface chemistry.

Hydrogen sulfide and sulfur-based odors

In contrast to ammonia, hydrogen sulfide (H_2S) is an acid, not an alkaline gas. Under mildly alkaline conditions, H_2S can be oxidized via microbes to other sulfur compounds such as DMS (dimethyl sulfide) and DMDS (dimethyl disulfide), which are more important odor sources than H_2S in compost (Rosenfeld and Henry, 2000). Acidic pH suppresses the dissociation of H_2S, limiting its oxidation to sulfur (Shang et al., 2013). While AC has been used to adsorb H_2S from various types of waste stream gases, AC needs to be treated with hazardous caustic chemicals to function well as an adsorbent for H_2S, which just adds to the already high cost of producing it. Additionally, the treated AC does not last long before it loses effectiveness and needs to be regenerated at further cost and risk of harm from hazardous alkali chemicals.

Because of these limitations, researchers have looked for less expensive forms of charcoal that could adsorb H_2S. Shang et al. (2013) compared AC to three different biochars in a packed column study. All of the biochars functioned better than the AC, with the most alkaline biochar, made from rice hull, performing the best. Shang hypothesized that surface functional groups, present on the biochars but not on the AC, changed the way H_2S was oxidized. This avoids the formation of sulfuric acid that limits AC's capacity for adsorption. However, the experiment did not allow for any conclusions to be reached on the actual mechanisms that produced greater H_2S sorption in biochars over AC. Others (Bagreev et al., 2001) have proposed that nitrogen-containing basic functional groups on biochar surfaces can facilitate the oxidation of H_2S. Interestingly, Steiner et al. (2010) found that poultry manure compost treatments with 20% biochar reduced the concentration of H_2S in the headspace volume by 71% and also that the final compost with biochar had retained more sulfur.

High carbon wood ash has also been examined. Depending on the carbon content of the wood ash, it can have many properties similar to AC, including high surface area. Rosenfeld and Henry (2001) used wood ash materials with different amounts of carbon (ranging from 0.24% to 32% carbon) in flux chambers to test their ability to adsorb compost odor gases. They found that the carbon content of the ash correlated well with the adsorption efficiency of various sulfur compounds (DMS, DMDS, DMS and CS_2) as well as ketones, another group of compost odor gases. In contrast, the sorption of both ammonia and tri-methylamine odors was more dependent on residence time than the carbon content of the ash. Das et al. (2003) conducted a controlled incubation study of a blend of biosolids and wood shavings to test different coal ashes, a wood ash and AC for control of sulfide emissions and found "a consistent decline in emissions with increasing carbon content of the ash amendments."

Aeration and moisture

As previously discussed, aeration and corresponding oxygen availability are key parameters that affect control of odorous compounds and overall compost treatment. Biochar can improve the aeration of compost piles with potential impacts on both odor generation and moisture regulation. As reported above, Yoshizawa et al. (2005) found that pore spaces in charcoal materials retain oxygen that helps sustain the microorganisms that carry out aerobic composting. Steiner et al. (2011) hypothesized that biochar as a bulking agent improves oxygen availability resulting in greater microbial activity. Testing 5% and 20% additions of pine chip biochar to poultry litter compost, they found that the addition of 20% biochar caused microbial respiration (measured as CO_2 emissions) to peak earlier and at a higher level than either the 5% or 0% biochar, confirming this hypothesis.

While air is held in biochar pore spaces and voids, water tends to be held on biochar surfaces through hydrogen bonds (Conte et al., 2012). Thus air and water do not exclude each other and both can be held within the porous structure of biochar. Depending on chemical surface properties, biochar will hold more or less water. In a study of the surface properties of composted biochar, Prost et al. (2013) placed litterbags of two types of biochar (gasification coke and charcoal) in compost. Both types of biochar adsorbed leachate generated during the composting process. They found that the moisture content of gasification coke increased from near zero to almost 100%, and that of charcoal increased from near zero to over 50%. This has implications for odor control because leachate escaping from compost piles is a potent odor source. Retaining moisture in biochar may help avoid formation of anaerobic pockets in the compost, which also reduces odor generation. Moisture is also the vehicle for bringing dissolved organic carbon and nitrogen compounds into contact with biochar surfaces. Steiner et al. (2010) measured the bulk moisture content of compost with additions of 0%, 5% and 20% biochar. Moisture content was increased in the control and the 5% biochar composts but decreased in the 20% biochar treatment over the compost period.

Methane

Methane is a potent GHG emitted by compost. Methanogenic microbes are anaerobic, so aeration, with biochar or other methods, can limit CH_4 generation. Sonoki et al. (2012) added approximately 10% biochar to a compost pile and assessed the presence of methanogens (CH_4 generating microbes) and methanotrophs (CH_4 oxidizing microbes) throughout the thermophilic phase of composting. They found that the level of methanogens was 2 times lower and the level of methanotrophs was 3 times higher in the piles with biochar.

Nitrous oxide

Nitrous oxide is another strong GHG that is a factor in many agricultural processes involving nitrogen, including compost. Nitrous oxide is formed during denitrification. Denitrification is the microbial reduction of nitrate into gaseous forms of nitrogen. The final product is N_2 gas that returns to the atmosphere, completing the nitrogen cycle. However, when the process is incomplete, other forms of gaseous nitrogen can be emitted to the atmosphere. The N-conversion processes in both soil and compost are complex and they depend upon several physicochemical and biological factors. Multiple studies have shown that biochar impacts emissions of N_2O when it is applied to soil (Van Zweiten et al., 2010; Taghizadeh-Toosi et al., 2011; Clough et al., 2013; Cayuela et al., 2013). In most, but not all cases, biochar has reduced N_2O emissions from soils, but the reasons why this occurs are not completely clear. Soil aeration, moisture, pH, N content, N immobilization by biochar, and soil chemistry have all been cited as important factors. Recent work (Cayuela et al., 2013) makes the case for biochar functioning as an "electron shuttle" that improves the transfer of electrons to soil denitrifying microorganisms, allowing them to complete the conversion of N_2O to N_2 gas.

Generally, the bulk of N_2O compost emissions occur in the later stages of composting when most of the consumable carbon has been used (Boldrin et al., 2009). Wang, et al. (2013) compared pig manure composted with wood chips, sawdust and 3% biochar by weight to pig manure composted without biochar. They found that the addition of biochar significantly lowered the total N_2O emissions, especially during the later stages of composting. They also found that the biochar addition altered the microbial populations in the compost, resulting in fewer N_2O producing bacterial and more abundant N_2O consuming bacteria.

Carbon dioxide

Carbon dioxide is emitted by compost as most of the biomass carbon in compost naturally decomposes to CO_2 and returns to the atmosphere. The carbon that is retained is converted to stable carbon compounds known as "humus". Studies of compost and biochar have found varying results for CO_2 emissions. The interest is not so much in the total amount of CO_2 emissions (since the CO_2 in the organics being composted has been relatively recently incorporated from the atmosphere). Instead, the interest has been as an indicator of microbial respiration and the time it takes for compost to reach maturity. Steiner et al. (2011) found that respiration peaked more quickly, and at a higher level, with 20% biochar additions. This result was not found in a treatment with 5% biochar. Tanaka et al. (2006) studied the influence of charcoal additions on the proliferation of microorganisms in a mixture of charcoal and rice bran and found that both the rate of increase and the total extent of microbes were dependent on the amount of charcoal added to the mix. Ogawa et al. (2010) said that his years of practical experience using biochar in compost in Japan confirmed that the more charcoal is used, the faster decomposition progresses.

Charting compost temperature over time is another way to gauge respiration (and therefore CO_2). When composting sewage sludge with varying percentages of bamboo biochar (0 to 9%), Hua et al. (2009) found very little difference in time and temperature curves over 42 days and little difference in total organic matter over time, except during the first few days. Jindo et al. (2012) found that while the time vs. temperature plot was similar for compost with and without 2% biochar, the biochar treatment increased the pile temperature during the thermophilic phase.

Nutrient balance and the C:N ratio can either promote or delay compost activity and respiration. Most biochars will not contribute much degradable carbon (Steiner et al., 2011) to the compost. This means that while biochar increases the total C:N ratio of the compost mix, the functional C:N may not be changed much at all.

As discussed in the next section, biochar promotes humification of the degradable carbon in the compost, leaving open the possibility of sequestering additional biomass carbon and reducing CO_2 emissions during composting. This potential could be tested by trying different "recipes" with different forms of degradable carbon combined with different amounts and types of biochar.

Biochar and compost quality

The quality of industrial compost is an ongoing issue. In a review of synergisms between compost and biochar, Fischer and Glaser (2012) state, "In spite of the potential and observed beneficial effects of compost application to agricultural soils, this technique is not widespread across Europe and especially in Germany, [where] low quality composts are produced due to inefficient waste management regulations." The authors propose improving compost quality through the addition of biochar. The benefits they suggest include "enhanced nutrient use efficiency, biological activation of biochar and better material flow management and a higher and long-term C sequestration potential compared to individual compost and biochar applications (negative priming effect)." Some of the C sequestration potential results from the long-term stability of biochar. The "negative priming effect" they refer to is the observation that total CO_2 emissions are lower from biochar-amended soils. One characteristic of the native *terra preta* soils of the Amazon is lower respiration combined with higher microbial biomass and greater microbial diversity. The implication is that biochar helps improve the metabolic efficiency of soil life forms, lowering CO_2 emissions (Thies and Rillig, 2009).

Fischer and Glaser propose an ideal modern biochar compost system (Figure 5.1) by looking at the genesis of the *terra preta* soils in the Amazon. The work of many scientists suggests that these blackened, fertile soils were human-created, not formed by natural forest fires or other processes (Glaser and Birk, 2012). Most likely they began as kitchen waste with the accidental accumulation of food scraps, ashes and manure, but as the populations grew (perhaps attracted by the newly created soil fertility of kitchen material), they began to organize and deliberately manage the material flows of plant biomass, mammal and fish bones, ash, biochar, and human excreta that resulted in the *terra preta* soils we see today. Based on this history, Fischer and Glaser propose the modern material flow management scheme diagramed in Figure 5.1 for producing high quality compost that will replenish carbon, nutrients and beneficial microbes in agricultural soils.

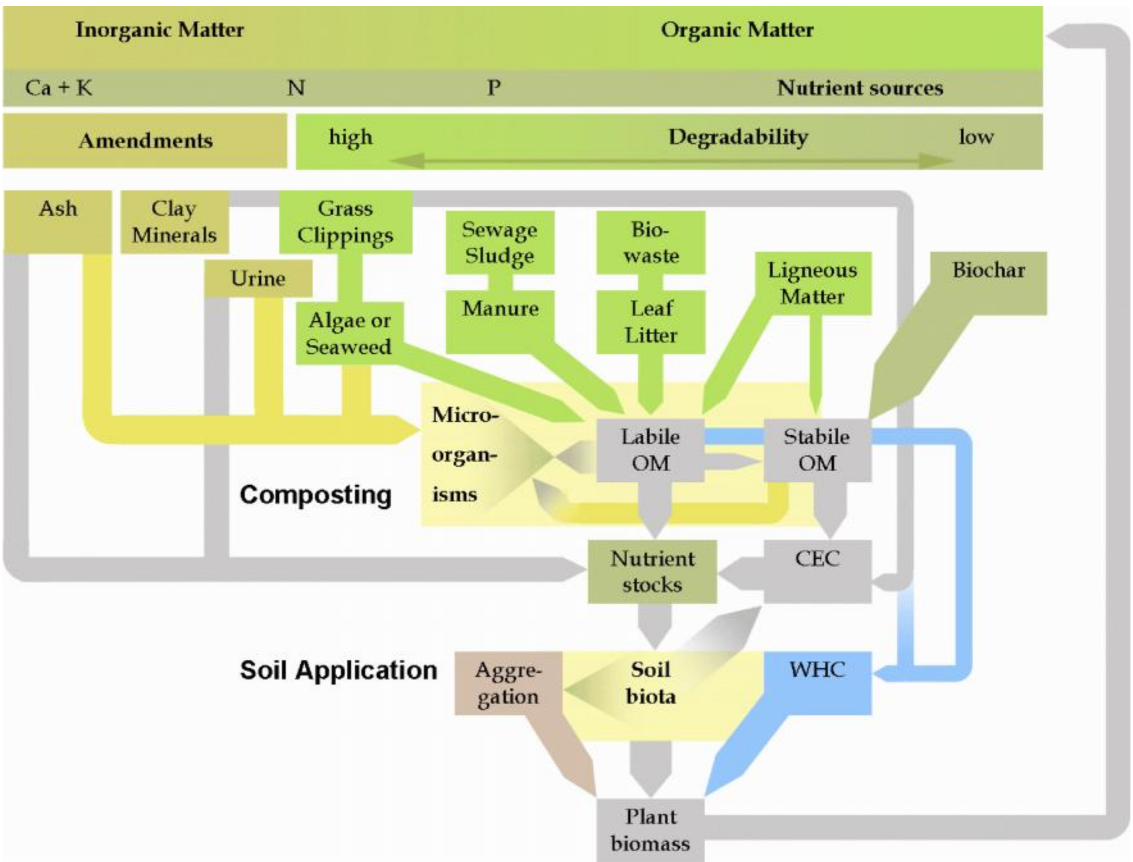


Figure 5.1: Sustainable management of natural resources by combining biochar with organic and inorganic wastes in compost processing (Fischer and Glaser, 2012)

Compost nitrogen content

Compost can lose nitrogen by volatilization of ammonia or other nitrogen-containing gases, or by leaching. As discussed previously, biochar can help retain ammonia. It also holds water, so can reduce leaching. Several authors (Spokas et al., 2011; Clough et al., 2013) have suggested biochar could be used to produce a new type of slow-release fertilizer, based on its ability to sorb nitrogen. Composting biochar with high-nitrogen feedstocks would be one way of accomplishing this. Results on nitrogen retention in biochar and compost have already been discussed, but they are summarized here: Steiner et al. (2010) found 20% biochar added to poultry litter compost reduced N loss by 52%. Chen et al. (2010) found that adding 9% bamboo biochar to pig manure compost reduced total nitrogen loss by 65% compared to the control. Hua et al. (2009) found that adding 9% bamboo charcoal to sewage sludge compost reduced total nitrogen loss by 64.1%.

Compost maturity and humic content

Several studies have looked at the effects of biochar on the stability and quality of final compost products. These studies have found that adding biochar to compost reduced the amount of dissolved organic carbon in mature compost while increasing the fraction of humic materials (Jindo et al., 2012; Dias et al., 2010; Tu et al., 2013). Following the addition of 2% biochar to compost, Jindo et al. (2012) recorded a 10% increase in carbon captured by humic substance extraction and a 30% decrease in water-soluble C. They also found an increase of fungal species diversity and proposed that these fungi were responsible for the increased humification.

Biochar property alteration through composting

Biochar has been shown to change compost properties, but the reverse is also true: composting can change biochar properties. Specifically, composting makes the surfaces of biochar more reactive and increases sorption properties. Prost et al. (2013) placed litterbags of biochar within active compost piles. They found clear increases in sorption properties from composting over a 6-month period. Borchard et al. (2012) also used litterbags of biochar in compost to assess two different biochars. They found that composting increased the sorption affinity coefficient of the biochars by 3 to 5 times for copper in a copper sulfite solution. This could be a concern where copper is needed as a trace element nutrient in soils. On the other hand, this could help immobilize metals present in sewage in China (Hua et al., 2009), producing a safer compost.

Plant growth response to biochar compost

Biochar amended compost has been found to improve several indicators of plant growth. At the conclusion of their experiment on biochar compost and CH_4 generation, Sonoki et al. (2012) performed a germination test on both the biochar compost and the control. They found a slight improvement of seed germination in the biochar compost. At the field level, Lashari et al. (2013) conducted a two-year field trial using poultry manure composted with biochar on a salt-stressed wheat field in China and found a significant decrease in salt stress along with crop yield improvement. The effect was increased during the second year of the trial.

Several studies (Fischer and Glaser, 2012; Schultz and Glaser, 2012; Liu et al., 2012; Steiner et al., 2008) have experimented with various combinations of compost and biochar soil amendments. All of these studies found improved plant growth when biochar was added to soil along with compost. A 2013 study (Schulz et al., 2013) looked instead at biochar composted together with other materials (including sewage sludge and green waste). They tested six different amounts of biochar in the compost (0 to 50% by weight), and also three different compost application rates. Using oats in greenhouse pots on two different soils (sandy and loamy), they discovered that plant growth was improved as the amount of biochar in the compost increased. They also found that growth improved with increasing application rates of each type of biochar compost.

Conclusion

Biochar is a promising ingredient for compost with the potential to improve the composting processes and reduce odor emissions. It can also create finished compost with greater value as a soil amendment and fertilizer. This is an expanding area of scientific and agricultural research and additional literature will be forthcoming. Further research and pilot projects are needed to achieve the following:

- Determine optimum application rates for biochar in composting, and minimum application rates to achieve desired effects.
- Test different biochar materials to determine the effects of properties such as surface area, ash content and volatile matter on compost processes and quality.
- Trial the use of different inoculants with biochar to assess their effects on odor control and other composting processes. Test the use of inoculants and biochar at food scrap collection points for the most effective odor control.
- Experiment with different combinations of feedstocks and biochar to determine impacts on odor generation, GHG emissions, nutrient retention and humification. Different "recipes" may be invented for composts with specific properties (e.g. slow release fertilizer).
- Carry out comparative field-testing of compost with and without biochar in different applications including agriculture, forestry and remediation.
- Assess different systems for economical production of biochar including installations at compost facilities that can use excess lignocellulosic material as biochar feedstocks.

Investigators should also evaluate the use of carbon-based materials at various points in the waste collection and process flow. Potential areas of biochar application include:

- Collection bins. Since these are unavoidably anaerobic, biochar inoculated with bokashi or similar microbial cultures could reduce odor.
- Receiving area. Adding biochar as a cover immediately after reception of waste could help control odor.
- Bulking agent. Biochar as a bulking agent in compost could help with aeration, leachate and moisture management and it can sorb odorous gases and in some cases prevent their formation.
- Add to cover. When biochar supplies are limited, it may be effective to add a layer of biochar as a cover on piles. This can be renewed after piles are turned, and the old cover will get incorporated with the compost.
- Add to biofilters. Biochar can help improve the adsorptive and odor-neutralizing function of biofilters. It can also reduce biofilter compaction and extend their life.

Finally, the comparative economics of biochar versus other odor control measures needs to be analyzed. This analysis should include not only the cost of acquiring (whether generated on site or purchased) and applying biochar, but also the potential for increased income from a higher quality compost product.

Conclusion

Food scrap collection is growing in importance with numerous municipalities in the US initiating residential or industrial programs in the last decade. This trend has the potential to contribute enormously to sustainable waste management in the US, with nearly one-third of all produced food wasted. However, this increased organics recovery has also had drawbacks. It has increased the processing burden on existing waste management infrastructure, particularly within the compost industry. In addition, the increasing percentages of putrescent material represented by food scraps have led to emerging odor concerns communities near compost facilities.

Composting is a biological process utilizing controlled, aerobic conditions within a mixed ecology to produce compost, a valued soil amendment. Finished compost has undergone an initial, rapid stage of decomposition; a longer stage of stabilization; and ultimately an incomplete process of humification (Insam and de Bertoldi, 2007). Odors are a result of compounds produced during the degradation processes, and can be produced before food scraps arrive at the facility, during compost handling and preparation, or during actual composting. Compounds primarily responsible for odors appear to be organic sulfides, mercaptans, amines, and VFAs. Terpenes, ammonia, alcohols, and hydrogen sulfide also contribute.

The composting literature indicates that composting of highly biodegradable material such as food scraps and fresh-cut green waste is highly prone to both low pH and shifts from aerobic to anaerobic conditioning. These risks are particularly acute during the first stage of processing. It is also a particular danger at compost operations with high flow rates and excessively large piles. In severe cases, these anaerobic cultures are also capable of producing VFA, lowering the pH, and continuing the shift in microbial population—reinforcing the negative cycle.

A large number of strategies can be used to limit odor generation and dissipate or treat odors before they impact the surrounding communities. Strategies fall generally within four categories:

- Enhancing emissions control infrastructure,
- Biological optimization of compost piles,
- Adding anaerobic pre-processing of highly biodegradable wastes, and
- Amending compost materials with carbon-based products.

First, non-biological structures, technologies and controls can be implemented throughout the compost production process. Some of the most important for controlling odors include next generation negative-air tipping buildings, covered structures as well as covered piles for the actual compost operation, use of multiple, staged biofilters and more rigorous design and engineering of facilities. Real-time process controls that monitor pile conditions and respond by adjusting aeration or other mechanisms are also likely to be important. It is important to note that each of these strategies increases costs and complexity of the operation.

Second, biological approaches can be used to enhance the composting process and improve biological control of odor. These methods are particularly important for ensuring that the first phase of composting proceeds quickly, and that aerobic processing is maintained. A summary of essential infrastructural and biological parameters and their optimal targets during composting of high fractions of biodegradable material are provided in Table 6.1. Some moderate to smaller size operations have also had success with high-value treatment, be it BCS, mushroom, or vermiculture.

Table 6.1: Suggested BMP parameters

BMP Parameters	Suggestions
Plan/Footprint	Size to handle flow rate; 2,000-3,500 ft^3 set back; 2-4% slope
Structures	Large NA tipping building, covered structures, biofilters
Composting Type	Micro-pore covers; aerated static pile
Process Controls	Complex, real-time monitoring many parameters & feedback
Aeration	Variable drive, phased 2,000+ to 200-500 cfh/dt
Oxygen Content	> 10-18%, but preferred on high end
Moisture	< 60%, more between 50-55%, pre-controls on food scraps
Temperature	Variable drive, phased 35ºC then 50-55ºC, no > 65ºC
Pile Size	No greater than 25' by 10' (width x height)
Mix/Nutrients/C-N Ratio	C/N 20-25; optimal Biodegradable C; 10-15% seed rate
Bulk Density/Porosity	2-3" particles; > 1,000 lb/yd^3 bulk; 40-60% air capacity

Third, a small but clear body of literature indicates important economic and environmental benefits that could result from integrating anaerobic digestion prior to composting, specifically for the treatment of highly biodegradable food scraps and fresh grass clippings. This could reduce odors, improve air quality, enhance organic recycling processing quality and performance, and reduce GHG emissions. Because the process also generates energy in the form of a biogas, it could help offset the energy needs of the composting operation. Remaining hurdles include improving technical performance for digestion of highly biodegradable wastes, and added costs and complexity of such facilities. Most importantly, less than optimal received electricity prices in the US have made it a challenge to develop economically viable projects, though researchers and project developers continue to make progress in this area. Further research could lead to advances in AD technology that could reduce costs, increase performance, or develop value-added co-products. Additional development of auxiliary technology, such as biogas conditioning and compression technology for generation of compressed CH_4 fuel, may create additional economic incentives. This may be a particularly appealing match for organics recycling facilities, as they could use the fuel in their waste management fleets.

The fourth major odor-control strategy includes incorporation of carbon-based materials to piles, including AC, high carbon wood ash, and biochar. Among these, AC is generally understood to be technically effective but too expensive for widespread use in compost odor control. High carbon wood ash is a waste product from biomass energy combustion, and is therefore obtainable at relatively low cost. Biochar, on the other hand, is expected to have costs somewhere between wood ash and AC.

The existing small amount of scientific literature on high carbon wood ash indicates mixed results. The product may provide some composting process benefits (e.g. faster processing, higher initial temperatures), and may reduce some odors, but may have no impact on, or may even increase others. In addition, at higher quantities, the ash may compromise the quality of the compost as a plant growth medium.

Meanwhile, research results are beginning to show how biochar can improve compost processes and reduce CH_4 emissions. Biochar can hold air and water at the same time, encouraging aerobic bacteria and reducing the number of anaerobic pockets that produce CH_4. Biochar also appears to support denitrifying organisms in ways that reduce the production of N_2O. Biochar can improve compost quality by retaining nitrogen and other nutrients and minerals. It promotes compost maturity and increased humification and may have positive climate impacts as more carbon is converted to stable humic substances. Recent studies suggest that biochar compost may have positive effects on plant growth. There are a number of ways that biochar could be used in current composting systems to reduce the generation and propagation of odors. These include adding it to anaerobic collection bins to suppress VFA generation, using it in compost receiving areas for immediate odor control, and using it as cover or a bulking agent in windrows. Biochar may also work to extend the life of biofilters and control leachate in compost yards. Any economic analysis of using biochar in compost should balance the cost of using biochar against increased returns from the sale of higher quality compost than is obtainable without biochar.

This study and literature review has summarized and detailed many of the areas and approaches that could be used by the industry to improve upon present aerobic compost treatment of organics enriched in large fractions of highly biodegradable waste such as food scraps and fresh yard clippings. While promising strategies for improving composting and controlling odors exist, it is important to recognize that each of these strategies involves greater levels of complexity, control and training, as well as increased capital and operating costs. Regulatory agencies will undoubtedly play a role as continued occurrences of odors come to the fore, with roles potentially including enhanced design criteria, regular reporting of on-line monitoring with feedback control, and establishment of maximum flow rates and processing times. They may also play a key role in facilitating agreements as well as education/outreach to make viable business plans placed under these new regulatory or capital structures. Addressing these issues may help ensure that communities can successfully and sustainably manage their organic wastes, while generating an invaluable soil resource.

Appendix A. Historical and Traditional Uses of Biochar Related to Odor Control

Ancient and traditional biochar

Biochar was re-introduced to the modern world largely as a result of the discovery of the human-created (anthropogenic) soils in the Amazon, known as *terra preta*. The genesis of these soils began 2000 to 2500 years ago (Neves et al., 2003). While geologists had been aware of these unusually black soils since the 19th century, it was not until the 1960s that soil scientists began investigating them, led by the Dutch soil scientist Wim Sombroek (Mann, 2008). Today, researchers have concluded that *terra preta* soils were created through the process of waste disposal. Formed by the combination of charcoal, ash, food scraps and human excreta, the expansion of these fertile soils facilitated the expansion of the human population in the Amazon (Glaser and Birk, 2012). Before the arrival of Europeans and their diseases (which decimated the indigenous people), the settlements along certain parts of the Amazon River and its tributaries were concentrated on high river bluffs above the flood plain. Some anthropologists estimate that there were as many people living in the region before Columbus as exist today—about 10 million (Bush and Silman, 2007). One can speculate that as the population expanded and the amount of human excreta and food scraps grew, it would have become ever more important to sanitize and de-odorize waste. It makes sense that charcoal would be valued and used for its ability to control odor in food scraps and human excreta and for the rich fertile soils that resulted.

Recent investigations into tropical regions in other parts of the world have found "anthropogenic dark earths" similar to the Amazonian *terra preta*. Researchers identified several sites in Borneo that shared many characteristics with *terra preta* soils including high carbon content, high fertility, and a concentration along riversides (Sheil et al., 2012). An ongoing survey of dark earths in Africa (Leach et al., 2012) has so far identified *terra preta* analogues at 134 sites in Liberia. Elsewhere in Liberia, Guinea, Ghana and Sierra Leone anthropogenic dark earths are described as "commonplace". Dark earths are being formed in these regions today through the ongoing addition to soil of various forms of char and ash along with crop waste, cooking waste and human excreta.

There is also a set of traditional practices that involve burning biomass in pits and trenches covered with dirt directly in the fields in order to improve soil fertility. These practices mix charcoal and ash into the soil. The process of heating the soil also affects nutrient cycling and physicochemical properties of the mineral soil. The use of covered biomass burning trenches has been reported by aid workers in the Batibo region of Cameroon (Reddy, 2009). Biomass charring is also still practiced in India and Bhutan, and was until recently in Spain (Olarieta et al., 2010).

Many traditional farming practices use fire to clear land ("slash and burn") or remove crop stubble. These practices are potentially a source of soil charcoal. However, in most cases the amount of charcoal is small compared to the amount of ash. Also, this sort of biomass burning does not involve the use of charcoal and ash to treat wastes such as food scraps, manure or excreta.

The traditional farming practices of China, Japan and Korea recycled massive amounts of human waste, ash, crop residue and other biomass into agricultural fields. In 1909, the American agriculturalist F. H. King embarked on an eight-month tour of China, Japan and Korea in order to view and document agricultural practices. The resulting book, *Farmers of Forty Centuries* has become an agricultural classic. Part of King's purpose in the book was to contrast the enduring agriculture of Asia with what he viewed as destructive and wasteful practices then advocated by the US Department of Agriculture (Paull, 2011). King declared, "One of the most remarkable agricultural practices adopted by any civilized people is the centuries-long and well-nigh universal conservation and utilization of all human waste in China, Korea and Japan, turning it to marvelous account in the maintenance of soil fertility and in the production of food" (King, 1911, p. 193). As an indicator of the commercial value of this human waste he found that the city of Shanghai sold concessions to waste haulers, charging one contractor $31,000 in gold for the right to collect 78,000 tons of human waste for sale to farmers outside the city (p. 194). He found compost making to be a high art in Japan where prizes were offered in each county for the best compost. Winners at the county level went on to compete for a prize for best compost in the prefecture (p. 397). Although he did not specifically describe the use of charcoal in these composts, he observed that ash materials were added in large amounts. Moved by the thrift and care for conservation of nutrients that he observed on his travels, King expressed his frustration with the wasteful practices of his own country, "When we reflect upon the depleted fertility of our own older farm lands, comparatively few of which have seen a century's service, and upon the enormous quantity of mineral fertilizers which are being applied annually to them in order to secure paying yields, it becomes evident that the time is here when profound consideration should be given to the practices the Mongolian race has maintained through many centuries" (p. 193). Contrasting these Asian practices with those in America he said, "The rivers of North America are estimated to carry to the sea more than 500 tons of phosphorus with each cubic mile of water. To such loss modern civilization is adding that of hydraulic sewage disposal..." (p. 197).

Some historical uses of charcoal in Japanese agriculture are documented in "Pioneering works in biochar research, Japan" (Ogawa and Okimori, 2010). Ogawa and Okimori describe a Japanese agricultural encyclopedia published in 1697 that gives instructions for making biochar compost, "After charring all waste, concentrated excretions should be mixed with it and stocked for a while. When you apply this manure to the fields, it is efficient for yielding any crop." Ogawa and Okimori claim that biochar has been in used in Asia since ancient times, and that rice husk charcoal has been used since the beginning of rice cultivation. Wood charcoal was not generally used in agriculture as it was too valuable as fuel. The article also reports, "The practice of using rice husk charcoal mixed with excreta had been very popular in wheat cultivation until about 100 years ago. There were double benefits, which are that the charcoal can absorb and retain chemical nutrients as well as deodorize excreta. However, this method was so commonplace for local people that scientists rarely paid enough attention to investigating it." Beginning in the 1980s, Ogawa and other scientists began to research these traditional uses of charcoal in agriculture in order to learn more about their effects. This revival of agricultural charcoal in Japan has been an important stimulus for the current attention to biochar.

One might expect that China would also possess historical texts on agricultural charcoal, but none have yet been published or described in English. Perhaps, as in Japan, the techniques were too common and widespread to attract much attention. However, archeological investigations may tell the tale. Recently, thick layers of charcoal were discovered in an ancient rice paddy, prompting researchers to speculate that these were analogous to *terra preta* (Wu, 2010).

Europe also has examples of ancient and historic use of charcoal in fields. Large extents of *plaggen* soils characterized by char particles and evidence of dung and other wastes can be found in Holland and elsewhere in northern Europe (Davidson et al., 2006). Wim Sombroek, the Dutch soil scientist who is most responsible for initiating the scientific investigation of *terra preta*, recognized the similarity of the *terra preta* to the *plaggen* soils of his homeland: "Wim Sombroek learned about soil as a child, during the *hongerwinter*—the Dutch wartime famine of 1944-45, in which 20,000 or more people died. His family survived on the harvest from a minute plot of *plaggen* soil: land enriched by generations of careful fertilization. If his ancestors had not taken care of their land, he once told me, the whole family might have died" (Mann, 2008).

19th century agricultural charcoal

While the scientific investigations into *terra preta* are very recent, there exists an extensive body of literature on the use of charcoal for both agriculture and sanitation beginning in the 19th century in Europe and America. In this section we describe this literature, some of the issues that it raised, and how they were resolved.

The science of agricultural charcoal in the West began with the German chemist, Justus von Liebig. Liebig used experiments with plants grown in charcoal to prove his point that plants got their carbon from atmospheric CO_2 and thus did not require humus as a source of carbon. He used charcoal as a growth medium because charcoal was the "most unchangeable substance known; it may be kept for centuries without change, and is therefore not subject to decomposition." (Liebig, 1841, p. 62) He found that plants could thrive in powdered charcoal, and concluded that if carbon was not obtainable from the charcoal, it must have come from the air.

Liebig also found that charcoal provided some unique properties when mixed with soil. He attributed the effects of charcoal to its porosity and ability to hold nitrogen in a plant available form. Charcoal, he said, "surpasses all other substances in the power which it possesses of condensing ammonia within its pores, particularly when it has been previously heated to redness. Charcoal absorbs 90 times its volume of ammonia gas, which may be again separated by simply moistening it with water." (Liebig, p. 90)

Liebig cited a series of hothouse experiments using mixtures of charcoal that gave fantastic results. "An addition of charcoal, for example, to vegetable mould, appeared to answer excellently for the Gesneria and Gloxinia and also for the tropical Aroideae with tuberous roots. The two first soon excited the attention of connoisseurs, by the great beauty of all their parts and their general appearance. They surpassed very quickly those cultivated in the common way, both in the thickness of their stems and dark color of their leaves; their blossoms were beautiful, and their vegetation lasted much longer than usual, so much so, that in the middle of November, when other plants of the same kinds were dead, these were quite fresh and partly in bloom." (Liebig, p. 208)

The hothouse experiments also revealed that charcoal could have dramatic effects plant health. "Pure charcoal acts excellently as a means of curing unhealthy plants. A Dorianthes excelsa, for example, which bad been drooping for three years, was rendered completely healthy in a very short time by this means. An orange tree, which had the very common disease in which the leaves become yellow, acquired within four weeks its healthy green color, when the upper surface of the earth was removed from the pot in which it was contained, and a ring of charcoal of an inch in thickness strewed in its place around the periphery of the pot. The same was the case with the Gardenia." (Liebig, p. 209)

Popular journals for horticulturalists and farmers soon took notice of these experiments, and 19th century publications are full of descriptions, articles and testimonials on the beneficial effects of charcoal in soil. Many of these journals are available online in digital form. Writer Steven Edholm has compiled some of the best references with links on his blog *Turkeysong* (Edholm, 2012).

Just a few of the many available examples show that charcoal was valued for horticulture, field crops, manure management, odor control and compost. Many of the writers also observed that crops grown on old charcoal manufacturing sites, or on the middens of Indian villages were especially abundant. Here are several quotes from this abundant literature:

“My attention was first drawn to the influence of charcoal, by the wonderful experiments of Baron Von Liebig, in the propagation of plants, and the facility with which cuttings were rooted in this substance. Its use became very general in Europe by amateurs and cultivators of plants… As a medium for storing up the volatile portions of manure and compost heaps … it has probably no superior… One of the most striking illustrations of its efficacy, when applied alone, that has come to my notice, was the experiment made by Mr. Hayward, of Sandusky, Ohio, … having prepared his coal by grinding in a mill, set apart seven lots of land for experiments, the soil and cultivation being precisely alike on each, except as it regarded the application of charcoal. The result was, that on the lots where fifty bushels of coal were applied, there were twenty-five bushels of wheat obtained, while on those lots where there was no coal applied the crop was only five or six bushels…." (Wilder, 1851)

“For two years past I have used some fifty loads each season of refuse charcoal, and being fully convinced that it pays, I wish to recommend it to my brother farmers. I have tried it on grass, corn and potatoes—have tried it alone and in the compost heap, and in all situations it has proved faithful to its trust. As a top dressing for grass, it gives a green color and luxuriant growth. Applied to half an acre of early potatoes the last summer, the yield was 75 bushels of as fine healthy potatoes as could be desired, that sold readily for one dollar per bushel, and yielded the best profit of anything raised on the farm.” (Unknown Author, The New Jersey Farmer, 1856)

“Charcoal, already well known to be of inestimable value as an absorbent or disinfectant, and likewise containing abundance of nutritious food for growing plants, has also a remarkable influence on the color of flowers. This fact is too well known to gardeners to require much repetition. A few years since, a New-Haven gardener tried the experiment of the use of charcoal on the health of plants in pots in his greenhouse, and said that he could not possibly see the advantage of continuing under the old system without it. The result of my experience is, that, when not using charcoal in growing roses, they have been more or less subject to mildew, and the roots of the plants more apt to be injured by fungus, whereas with the free use of that material they are not liable at all to be attacked." (Unknown Author, The Horticulturist, 1869)

“In the midst of the disastrous drouth of last summer, while crossing a field in Moriah, occupied by Mr. Richmond, in pursuit of some Durham cattle I wished to examine, I observed a lot with its surface deeply and singularly blackened. Upon inspection I found it thickly strewn with pulverized charcoal. The field presented a rich verdure, strongly contrasting with the parched and blighted aspect of the adjacent country.” (Unknown Author, New York State Agricultural Society, 1853)

“Poudrette (night-soil deodorized with charcoal dust) is one of the best manures for the rose… Charcoal dust is an excellent surface dressing; it imbibes and retains moisture, keeps the plant healthy and intensifies the color of red varieties” (Turner, 2012, p. 72).

“A dead rat, nicely buried in a cigar box so as to be surrounded at all points by an inch of charcoal powder, decays to bone and fur without manifesting any odor of putrefaction, so that it might stand on a parlor table and not reveal its contents to the most sensitive nostrils” (Unknown Author, The Garden, 1873).

The entry on agricultural charcoal in A Cyclopedia of Agriculture (Morton, 1855) runs to ten pages and covers most of the topics mentioned above. On odor it says, “Charcoal also possesses the property of absorbing and retaining the odoriferous and coloring principles of most organic substances… From this deodorizing property, charcoal is frequently mixed with night soil, and other decaying manures; which it keeps free from smell, and at the same time aids in preserving, by absorbing the gases which would otherwise escape.“

The sewer debates

Like F. H. King, Justus von Liebig was an admirer of Chinese farmers and their attention to capturing nutrients from human waste. He said, "When human excrements are treated in a proper manner, so as to remove the moisture which they contain without permitting the escape of ammonia, they may be put into such a form as will allow them to be transported, even to great distances.” (Liebig, p. 197) Liebig acknowledged the efforts in many European cities to manufacture fertilizers from human waste but found that "the manner in which this is done is the most injudicious which could be conceived." He said, "In Paris, for example, the excrements are preserved in the houses in open casks, from which they are collected and placed in deep pits at Montfaucon, but are not sold until they have attained a certain degree of dryness by evaporation in the air. But whilst lying in the receptacles appropriated for them in the houses, the greatest part of their urea is converted into carbonate of ammonia… and the vegetable matters contained in them putrefy; all their sulphates are decomposed… The mass when dried by exposure to the air has lost more than half of the nitrogen, which the excrements originally contained…"(Liebig, p. 198).

The manufacture of these human manure products was a burgeoning industry in the 19th century. The major product, "poudrette," was named after a French term meaning "crumbs" or "powder". It was made from the contents of "dry closets" (as opposed to "water closets") that were hauled to the outskirts of cities and mixed with various additives such as ashes, peat, gypsum, clay, lime or charcoal. Depending on the admixtures and the process for incorporating them, the results were more or less valuable as a fertilizer.

An 1858 article in the London Chemical Society Journal (Campbell, 1858) reviews a number of patents and proposals for converting sewage into fertilizer. Charcoal and other carbonaceous materials feature prominently and it was recommended that carbonaceous materials be obtained from manufacturing wastes "along with the refuse of a great many trades." These included coal tar, road sweepings and the wastewater from tan-yards, for instance. Given the lack of standards and quality controls, it is no surprise that the majority of this "poudrette" was of suboptimal value and may in fact have been contaminated with toxic chemicals.

Here is one sample of the discussions about poudrette that can be found in 19th century agricultural journals: "Hon. J. Schull inquired in reference to the value of poudrette, and whether it was advisable for farmers to purchase and apply it upon farms. Mr. Whitman said there was no doubt as to the great value of a good article of poudrette. We make it by mixing with the night soil, copperas, charcoal and muck. When thus made, it is a very powerful fertilizer. But the poudrette of commerce is of very doubtful character. I had purchased some, and found it nothing more than the sweepings of blacksmith shops; or horse droppings, mingled with dust and dirt. Such poudrette was of no account." (Unknown Author, New York State Agricultural Society, 1868)

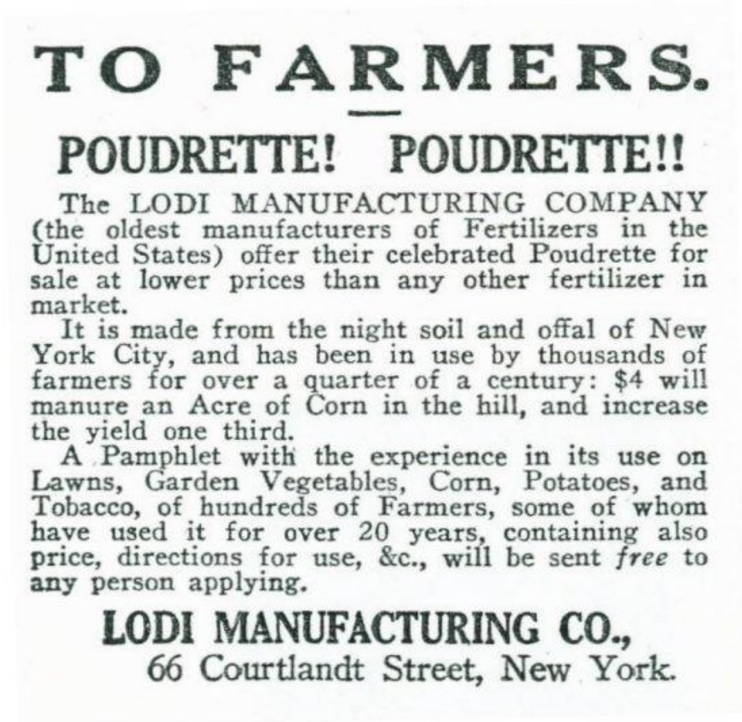
Eventually, the manure manufacturers also had to compete with the convenience of the "water closet" - the flush toilet. The first English patent for a flush toilet was issued in 1775. While cities in Europe and America had long had drainage systems for storm water and household gray water, they were not intended for human waste, and many cities had laws against disposal of excreta in sewers (Stoner, 1977). But as the wealthy segment of society rapidly adopted the new flush toilets, sewers began carrying increasing amounts of human waste. By the 1840s, cholera was epidemic in London. It all came to a head in 1858, when a hot summer produced what was afterward called "the Great Stink" (Lemon, undated). London shut its doors and windows, business ground to a halt and the government finally passed laws to plan an overhaul of the London sewerage system.

In 1858 the innovative Irish architect, Jasper Wheeler Rogers, issued a broadside titled "Facts and fallacies of the sewerage system of London, and other large towns." Rogers said, "The problem for the engineer to solve is, how can 3,000 tons of town guano be returned daily to the disinfecting soil, from which it was chiefly taken, with the least offense to health and with the least cost? Shall it be distributed by pipes or by railways? Shall it be disinfected by water, earth, ashes or any chemical compound? Under the present arrangements some hundreds of thousands of tons of this matter lie in store in London, putrefying in cesspools, and percolating the streets, while the residue is thrown into the Thames at great cost." (Rogers, 1858)

Rogers thought he had the answer. Ever since he had read about Liebig's work with charcoal and plant growth, he had been convinced that peat charcoal was the solution to the waste problem. Peat charcoal could also solve another great problem in his native land: famine. Unemployed farmers needed work so they could purchase food and avoid starvation. Rogers envisioned an industry to employ thousands in converting peat to charcoal that could then be used to deodorize the filthy sewers of Dublin, London and other towns, and he lectured widely to promote his ideas. At one lecture in 1849 attended by 600 people, he gave a demonstration, mixing peat charcoal with foul-smelling night soil. As a newspaper reported, "a few minutes before, all noses were turned away from the tin buckets in which the night-soil was brought; a few minutes after [it was mixed with peat charcoal], it was taken up in handsful and put into paper bags provided, and ‘stowed away,’ possibly in the same pocket with the pocket handkerchief." A panel of appointed judges then signed a certificate. "We the undersigned…. do unanimously decide as follows: That Mr. JW Rogers has fully proven the deodorising power of Peat Charcoal upon Human Excrement." (Rogers, 1858)

As a result of lobbying by Rogers and his supporters, the Irish Amelioration Society was established by Royal Charter in 1849, and in 1850, the Society opened a manufacturing center in Kildare County with a peat drying system and retorts to produce the peat charcoal, immediately employing 300 people. The plan was to open a hundred such facilities throughout Ireland. (Unknown Author, The Farmers Magazine, 1850)

But Rogers’ system never took hold. Perhaps the cost of manufacturing and transporting the peat charcoal to London was too high, or perhaps the convenience of the water closet was too seductive. By 1876, a report to Parliament with recommendations on sewage disposal methods came down firmly on the side of hydraulic sewage systems. They concluded, "None of the manufactured manures made by manipulating town's refuse with or without chemicals, pay the contingent costs of such modes of treatment." (Local Government Board, 1876, p. xii)



TO FARMERS.

POUDRETTE! POUDRETTE!!

The LODI MANUFACTURING COMPANY (the oldest manufacturers of Fertilizers in the United States) offer their celebrated Poudrette for sale at lower prices than any other fertilizer in market.

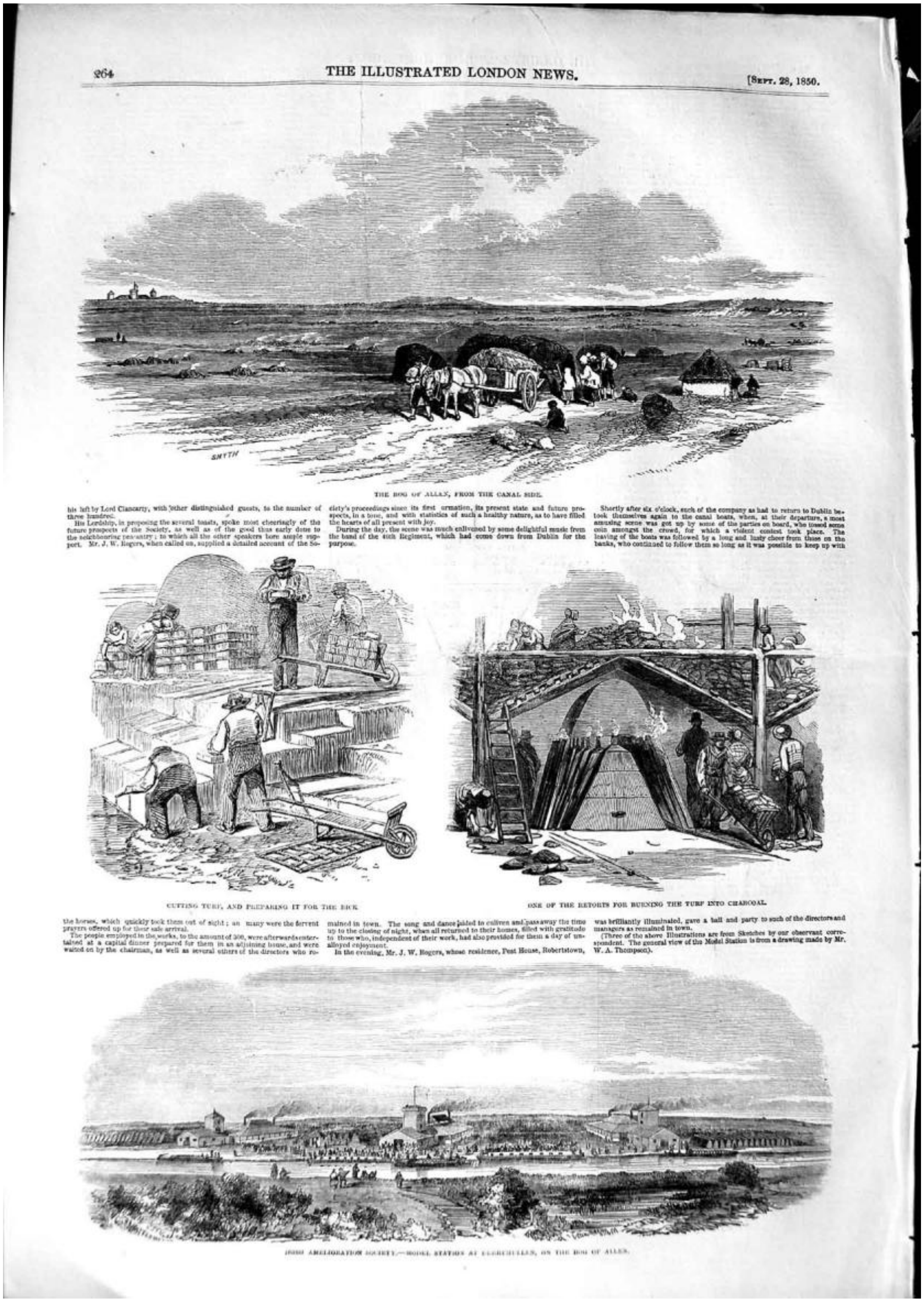
It is made from the night soil and offal of New York City, and has been in use by thousands of farmers for over a quarter of a century: $4 will manure an Acre of Corn in the hill, and increase the yield one third.

A Pamphlet with the experience in its use on Lawns, Garden Vegetables, Corn, Potatoes, and Tobacco, of hundreds of Farmers, some of whom have used it for over 20 years, containing also price, directions for use, &c., will be sent *free* to any person applying.

LODI MANUFACTURING CO.,
66 Courtlandt Street, New York.

Figure 1A: Advertisement for poudrette made from human night soil and other ingredients manufactured by the Lodi Manufacturing Company in the United States in the 19th Century. (International Plant Nutrition Institute, 2003)

Figure 2A: Cartoon depicting London's Great Stink of 1858: "In the summer of 1858, a combination of high temperatures and sewage overflow unleashed water-borne diseases and a malodorous stench on England's capital. This Punch magazine cartoon depicts 'Father Thames' introducing his offspring -- diphtheria, scrofula and cholera --to the City of London." (History, 2013)


264 THE ILLUSTRATED LONDON NEWS. [SEPT. 28, 1850.

SMYTH

THE BOG OF ALLAN, FROM THE CANAL SIDE.

his left by Lord Clancarty, with other distinguished guests, to the number of three hundred.

His Lordship, in proposing the several toasts, spoke most cheeringly of the future prospects of the Society, as well as of the good thus early done to the neighbouring peasantry; to which all the other speakers bore ample support. Mr. J. W. Rogers, when called on, supplied a detailed account of the Society's proceedings since its first ormation, its present state and future prospects, in a tone, and with statistics of such a healthy nature, as to have filled the hearts of all present with joy.

During the day, the scene was much enlivened by some delightful music from the band of the 4th Regiment, which had come down from Dublin for the purpose.

Shortly after six o'clock, such of the company as had to return to Dublin betook themselves again to the canal boats, when, at their departure, a most amusing scene was got up by some of the parties on board, who tossed some coin amongst the crowd, for which a violent contest took place. The leaving of the boats was followed by a long and lusty cheer from those on the banks, who continued to follow them so long as it was possible to keep up with

CUTTING TURF, AND PREPARING IT FOR THE RICK.

ONE OF THE RETORTS FOR BURNING THE TURF INTO CHARCOAL.

the horses, which quickly took them out of sight; an many were the fervent prayers offered up for their safe arrival.

The people employed in the works, to the amount of 300, were afterwards entertained at a capital dinner prepared for them in an adjoining house, and were waited on by the chairman, as well as several others of the directors who remained in town. The song and dance aided to enliven and pass away the time up to the closing of night, when all returned to their homes, filled with gratitude to those who, independent of their work, had also provided for them a day of unalloyed enjoyment.

In the evening, Mr. J. W. Rogers, whose residence, Peat House, Robertstown, was brilliantly illuminated, gave a ball and party to such of the directors and managers as remained in town.

(Three of the above Illustrations are from Sketches by our observant correspondent. The general view of the Model Station is from a drawing made by Mr. W. A. Thompson).

IRISH AMELIORATION SOCIETY.—MODEL STATION AT [illegible], ON THE BOG OF ALLEN.

Figure 3A: In 1950 the Irish Amelioration Society opened a facility on the Bog of Allen in Derrymullen, Ireland to convert peat to charcoal to sanitize the sewers of London and employ impoverished Irish farmers. From The Illustrated London News, September 28, 1950. Top: the Bog of Allen, from the canal side. Middle Left, cutting turf, and preparing it for the rick. Middle Right, one of the retorts for burning the turf into charcoal. Bottom, a view of the facility

Profiles of current initiatives for using biochar in compost

In this section we review a number of current projects that are either researching, experimenting with or actively using biochar in compost or waste treatment. Many, but not all, of these projects were inspired by the research results published since 2000 on using biochar as a soil amendment. Some of these projects are commercial operations. Some are the result of economic development projects or waste reduction initiatives. And some are driven by the desire of farmers to find better alternatives to current soil amendments and waste management practices.

Japanese composting with biochar

The revival of biochar practices in Japan in the 1980s corresponded with the growing concern in many modern industrial societies to divert waste from landfills. Japanese researchers and companies have started a number of projects and enterprises that are using biochar, mostly in combination with microbial inoculants, to convert food scraps, manure and other organic waste streams into fertilizers and soil amendments.

Makoto Ogawa is one of the leaders in the Japanese revival of biochar. In his article, “Pioneering works in biochar research, Japan,” (Ogawa and Okimori, 2010) he says, "In Japan, compost making from litter and excretions has been very common for a long time. Ash or carbonized material was an essential material to accelerate the decomposition stimulating the bacterial activity and neutralizing the acidity. It is also well known that the charcoal absorbs smell and liquid." The article also includes a description of a company that has been selling a composted biochar and chicken manure product since the 1980s. The product is reported to suppress plant root diseases and is sold as a biological fungicide.

For the most part, information on Japanese projects is difficult to find in English. However, in 2010, a delegation from the United Kingdom Biochar Research Centre (UKBRC) traveled to Japan to learn about a number of biochar initiatives. Their report on the mission (Masek et al., 2010) describes a food scrap composting system near Tokyo that processes 60 tons per day of material with 85% water content in aerated cylindrical containers heated to 70 degrees C. When the project added 3% biochar along with a sawdust bulking agent to their feedstock, it cut the composting time by two-thirds, to 10 days. The Japanese Agricultural Safety Bureau has approved the compost for use as fertilizer. The report also describes several manure composting facilities using biochar. The report is available on the site of the Japan Biochar Association http://www.geocities.jp/yasizato/JBA.htm). Some pages are available in English, including a bibliography of Japanese biochar research.

As biochar research in Japan matured in the 1990s, Japanese international aid programs began to disseminate biochar techniques to other Asian countries including Indonesia, Philippines, Korea, Taiwan, China and Thailand. One country that also received this technology was Costa Rica. Today, a farming cooperative there is manufacturing an organic fertilizer made from sugar cane bagasse biochar, chicken manure, rice husks, molasses and bokashi. Bokashi is a Japanese microbial inoculant that is often used in conjunction with biochar as a carrier. It is patented and trademarked as "Effective Microorganisms" or "EM-1". The technology was brought to Costa Rica by a Japanese volunteer in the 1990s (Soto and Joseph, 2009).

Integrated solutions in Vietnam

In Vietnam, Dr. Paul Olivier of Engineering, Separation and Recycling LLC (www.esrla.com) has been working to solve interconnected problems in waste utilization, sanitation and agriculture. Biochar is an integral part of the low tech, distributed solutions that he is disseminating through pilot projects that are described in his report, *Making Waste our Greatest Resource: The Small-Scale Production of Food, Fuel, Feed and Fertilizer* (Olivier and Hyman, 2011). All of this work is based on the principle of recycling food scraps as quickly as possible back into the food chain. For instance, large amounts of food scraps from restaurants or stores should be fed to pigs, not composted. If the waste will putrefy before it can be transported, it should be lacto-fermented to preserve the nutrients for the pigs. Pig feces are then fed to black soldier fly larvae (BSF) housed in bins, and the residue from that process is vermicomposted. BSF are valuable as animal feed or as a source of high quality lipids for industry. According to Olivier, these lipids are worth $1000 per ton. Biochar is added to the pigs' feed and used in their stalls for odor control. Biochar then cascades through the system and ends up in the vermicompost. At the household scale, mesophilic compost bins should use biochar to reduce odors and retain nutrients. Olivier also recommends the use of the "biochar urinal" - a simple bucket with biochar - to capture nitrogen and phosphorous in biochar and reduce odor. This can be added to the household compost bin.

Oliver's vision is all encompassing and he anticipates the day when Vietnam (a country where two-thirds of the work force is agricultural) will have completely integrated its waste management systems with sustainable agriculture. To do this will require "waste resource centers, extension services, co-ops, and regulatory agencies – all operating in close collaboration with one another."

Waste utilization in rural India

Dr. N. Sai Bhaskar Reddy of the Geoecology Energy Organisation (GEO) has designed a number of technologies to convert rural waste into biochar and compost for agriculture. The GEO website (www.e-geo.org) is the portal to a wide array of photos and reports on experiments with small farmers using biochar in different applications. There are designs for biochar-making stoves and biochar urinals, recipes for biochar compost and reports on field trials. According to Dr. Reddy, adding charcoal to soil is an ancient practice in India; charcoal and ashes from cook stoves were traditionally added to compost. He says, "Although the addition of charcoal to the soils was existing as a practice, but it was not explicit, it remained as part of traditional best practices in India. As we explore more and more evidences are visible and prove that the Indian farmers were using charcoal since hundreds of years. Because of such good practices agricultural activity is still sustainable in many parts of India."

The Delinat Institute, Switzerland

The Delinat Institute for Ecology and Climate Farming (http://www.delinat-institut.org/en/home) is a non-profit research foundation in Valais, Switzerland that is known for their work on soil carbon sequestration and their expertise in the post production treatment and use of biochar. The institute coordinates the European working group on biochar characterization and certification. It also publishes the Ithaka Journal (accessed at www.delinat-institut.org—ithaka-journal), reporting on experimental work and practical applications of biochar in farming. In *Ways of Making Terra Preta: Biochar Activation* (Schmidt, 2011) the author recommends compost as "the best way to produce terra preta and similar substrates. Microbial stimulation is highest in compost: nutrients are built into complex organic compounds and the final substrate is very close to the soil's humus."

Research at the Delinat Institute has found that addition of biochar to compost significantly improves the stabilization and conversion of ammonia to plant available nitrate. Their results show that an application rate of 10% biochar to biomass in the compost pile is effective. Delinat Institute is also using biochar to treat animal manure for odor control and stabilization, and conducting field trials with biochar and compost. Many results have been reported in presentations at various symposia, but much remains to be published, as the work is ongoing.

Sonnenerde Company, Germany

Sonnenerde (http://www.sonnenerde.at/) is an Austrian company that produces high quality green waste compost. They have been experimenting with biochar as a compost additive since 2009. In a series of experiments with different amounts of biochar and other additives like rock flour and sulfur, they found that the more biochar was added, the more carbon and nitrogen were retained in the material, and an addition of 10% biochar produced measurable benefits. A successful recipe to produce high quality compost is a combination of 5–10% rock flour plus 20% biochar (both by weight) in the compost mix (Dunst, 2013).

Sonnenerde operates a pyrolysis machine to produce biochar at their composting facility for use onsite. They also sell biochar to farmers who use it to condition cattle manure before applying it to fields. The biochar retains nitrogen for the crops and eliminates the smell of manure in the countryside.

Terra Preta Sanitation Initiative

At the Wastewater Management and Water Protection Institute at the Hamburg University of Technology in Germany, researchers have formed the Terra Preta Sanitation Initiative (http://www.tu-harburg.de/aww.html). They are exploring ways of using biochar to compost and sanitize human waste in developing countries with sanitation problems. One example of their work is a design concept for composting human waste with biochar in Moldova, a region where farmers have traditionally incorporated human waste into soil. Their research is aimed at using biochar to improve on current practices that result in odors and nutrient loss (Andreev et al., 2012). The Institute is hosting the First International Conference on Terra Preta Sanitation in Hamburg, on August 29–30, 2013.

European Biochar Research Network

Funding from the European Union is supporting a network of academic and industrial partners in the European Biochar Network (eBRN) (http://cost.european-biochar.org/en/home) to "expand and interconnect knowledge in biochar systems, to assess environmental impacts of biochar use and thus sharpen a promising global change mitigation tool up to the stage where economically feasible application will begin." Within the funding action (which runs from 2012 to 2016), there are two sub-programs that directly address biochar and waste management.

The REFERTIL project is targeted to small and medium enterprise companies "to improve the currently used compost and biochar treatment systems, towards advanced, efficient and comprehensive biowaste treatment and nutrient recovery process with zero emission performance. The improved output products are safe, economical, ecological and standardized compost and biochar combined natural fertilizers and soil amendment agricultural products used by farmers."

The mission of the FERTIPLUS project is to reduce use of mineral fertilizers and agrochemicals by "recycling treated organic waste as compost and biochar." The program activities include an assessment of the quantity and quality of biowaste across Europe; research on the sustainable production of both compost and biochar; an agronomical evaluation of biochar, compost and biochar blended compost; assessing the impact on carbon and nitrogen cycles and other ecosystem processes; LCA and best practices. The program also includes a knowledge transfer and dissemination component.

International conference on biochars, composts, and digestates

Research on biochar and compost is still at an early stage. However, it is a sign of the growing importance of this topic that the first conference devoted to biochar has now been scheduled. The International Conference on Biochars, Composts, and Digestates. Production, Characterization, Regulation, Marketing, Uses and Environmental Impact took place from October 17–20, 2013 in Bari, Italy (http://www.bcd2013.eu/). The scientific program is organized into four sections:

- Production technologies of biochars, composts and digestates by conversion of solid and fluid biowastes/biosolids,
- Analysis and characterization of biowastes, biochars, composts and digestates,
- Sustainable uses, applications and environmental impact of biochars, composts and digestates, and
- Certification, regulation and marketing of biochars, composts and digestates.

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