Review of composting and anaerobic digestion of municipal solid waste and a methodological proposal for a mid-size city

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ABSTRACT: Composting industry is a progressive and innovative industry that has been growing worldwide, especially in the last 20 years. Firstly, in this paper, an overview of fundamentals and processes on composting and anaerobic digestion are compiled, showing the versatility and multivariable profile of these processes. Secondly, a methodological proposal for a mid-size city is presented. It is proposed that the biodegradable part of the municipal solid waste, called BSW, can be efficiently composted with wastewater sludge, wood ash, coal ash, lime-kiln dust, and/or limestone quarry dust to improve the profile of the compost. In addition, anaerobic decomposition followed by vermicomposting is pointed as one of the best and efficient MSW treatment system, since it may reduce total time of the composting process. Furthermore, it generates liquid fertilizer and biogas, which provides energy to supply the composting plant. This makes the plant auto-sustainable in energy. Finally, an outline using real data from the City of Milwaukee, Wisconsin, USA, is being presented to illustrate an example of this proposed methodology of efficient composting.

1 INTRODUCTION

The "Garbage" is one of the major challenges in the world, especially in the cities and other population centers. Municipal solid waste (MSW) management is being considered a luxury item due to a variable quality of the service as a consequence of a combination of lack of resources, lack of expertise, lack of political will, and inadequate legislation [Fourie 2006]. In the last two decades, MSW management is one of the main public subjects under discussion. In the literature, researchers have been sharing case-studies about waste management practices in many different countries [Magrinho et al. 2006]. Many cities in developing Asian countries have difficulties for managing their solid waste. More than 90% of MSW in India is disposed of on the land unsatisfactorily [Sharholy et al. 2006]. In North America, the cost of MSW represents a multibillion-dollar industry [Huang et al. 2004]. Incineration and landfiling are some possible ways of dealing with Municipal Solid Waste; however, there is a better option, composting of MSW. This is a recent field in the U.S. In 2000, it was reported that there were 16 operating facilities in the U.S. that compost Municipal Solid Waste; all these are aerobic systems [Block & Goldstein 2000]. Anaerobic composting is not well used in the U.S until now [Goldstein 2004]; in contrast, anaerobic composting has been underway in Europe for food residuals for over 30 years especially as a solution for dwindling landfill space [Nichols 2004].

In 2003, MSW generation was estimated to be 4.5 pounds (2.04 kg) per person per day. Approximately 55% of the 240 million tons (2.4×10^8 kg) of MSW generated per year were landfilled, 14.0% were combusted, and 31% were recycled or composted [USEPA 2003]. Composting industry has grown in the USA in the past 20 years [Coker & Goldstein 2004]. Recycling of MSW increased 9% and composting of MSW increased 5% from 1990 to 2003, totaling 7% for composting [USEPA 2003]. Just to have an idea how much of an impact MSW has, residential waste of City of New York is approximately 28% composed of leaves, grass, yard, food, and other organic waste. New York could save $12 million per year by restoring and expanding composting programs [Goldstein & Goldstein 2004].

Therefore, sustainability is the key-word of this proposal. "Garbage" should not be thrown away because it is possible to generate compost from MSW, while producing energy from one of the by-products of the process, the methane gas ("cleaner energy") and harvesting materials from MSW to either recycle or reuse in cement industry. For instance, broken glass can be used as a finely ground mineral additive (FGMA) in cement, and up to 70% of portland cement clinker can be replaced with broken glass [Sobolev et al. 2006]. In addition, it is proposed to use residues from other industries, such as wastewater sludge, wood ash, coal ash, lime-kiln dust, and/or limestone quarry dust to co-compost with BSW.

2 OVERVIEW OF COMPOSTING AND ANAEROBIC DIGESTION– FUNDAMENTALS AND PROCESSES

There are three major biological management of MSW: biological processes occurring in landfills, anaerobic digesters, and composting facilities [Palmisano & Barlaz 1996]. In this paper, landfills will not be covered since there is a tendency of diverting biodegradable components from MSW from landfills to other alternatives, such as composting [Braber 1995, Harrison & Richard 1992, Komilis 2006, New Mexico State University 2004] and anaerobic digestion [Braber 1995, Shin et al. 2000]. This tendency is not only due to dwindling landfill space [Nichols 2004, Shin et al. 2000, Song & Greenway 2005, Tinmaz & Demir 2006], but also due to certain challenges, such as emanating odors, attracting vermin, emitting toxic gases, and potentially contaminating groundwater [Shin et al. 2000]. However, it is important to note that there are some studies that have proposed improvements in the challenges associated with landfills [Münnich et al. 2006].

Composting is the biological decomposition and stabilization of organic substrates that involves aerobic respiration [Palmisano & Barlaz 1996] and produces a final product that is stable, and free of pathogens and plant seeds that can be beneficially applied to land [Haug 1993]. During the process of aerobic composting, it generates carbon dioxide, water, and heat. On the other hand, anaerobic digestion is the biological decomposition of organic substrates in the absence of oxygen. During the process of anaerobic digestion, it generates methane, carbon dioxide, and numerous low-molecular weight intermediates such as organic acids and alcohols [Haug 1993] and humus [Chynoweth & Pullammanappallil 1996]. This implies that significantly less energy is required per mass of organic decomposed during anaerobic digestion compared to aerobic composting. Anaerobic digestion of MSW has developed more rapidly in Europe in the last decade than in the U.S. [Palmisano & Barlaz 1996]. Anaerobic digestion is also preferred in other countries, such as Korea, to manage food residuals [Shin et al. 2000]. Within the projects reported in the U.S. that turn methane from anaerobic digestion into electricity, there is a very good example of the Straus Family Creamery in California that generates up 600 000 kWh/year from anaerobic digester, saving $6,000/month in energy costs [Goldstein 2004].

2.1 *Biological fundamentals*

In anaerobic digestion, four different types of microorganisms are responsible for the the degradation of MSW: hydrolytic, fermentative, acetogenic, and methanogenic [Braber 1995]. In the first step of anaerobic digestion (depolymerization), the hydrolytic bacteria are responsible for depolymerization of polymeric solid substrates into smaller molecules such as organic acids, alcohols, and the methanogenic substrates. Some bacteria involved in this step are: Bacteroides *succinogenes, Clostridium lochhadii, Clostridium cellobioporus, Ruminococcus flavefaciens, Rumminococcus albus, Butyrivibriofibrisolvens, Clostridium thermocellum, Clostridium stercorarium,* and *Micromonospora bispora.* In anaerobic digesters with MSW, the predominant bacteria are *Clostridia*. In this stage, typically only 50% of the organic matter is degraded. Also, some intermediate reactions occur: for example, products of depolymerization reactions are converted to fermentation products [Chynoweth & Pullammanappallil 1996].

The last step is the methanogenesis. Methanogic bacteria are slow-growing anaerobes that degrade acetate, methanol, carbon dioxide, formate, carbon monoxide, methylamines, methyl mercaptans, and reduced metals [Chynoweth & Pullammanappallil 1996].

A variety of microorganisms are present in a composting system. Even though the microbial population may be vast, the main microorganisms that affect the composting system are fungi, actinomycetes, and bacteria. Also present are protozoa and algae [Stoffela & Kahn 2001]. Bacteria and fungi are the most important microorganisms for composting [Haug 1993].

A composting system may contain three classes of microorganisms: cryophiles or psychrofiles, mesophiles, and thermophiles [Stoffela & Kahn 2001]. Cryophiles bacteria do their best work at about 13ºC, although they work even until -20ºC. Between 0ºC to 40ºC, mesophilic bacteria predominate. Above this temperature, thermophilic bacteria work faster. When the temperature of the compost comes down, mesophilic bacteria again predominate [Wassenaar 2003].

Considering a windrow system, mesophiles and thermophiles are the most common microorganisms in composting, contributing to composting at different times of the process. This has four different stages. In the first stage, there are abundance of substrate and mesophiles that are predominant and very active. During this stage, large quantities of heat energy are generated, which increases the temperature of the compost pile. The favorable temperatures to this kind of microorganism are between 35°C and 45°C [Miller 1996, Stofella & Kahn 2001].

As the temperature rises, it becomes more favorable to thermophiles, for which the best temperature is higher than 45°C. The compost pile reaches about 65°C to 70°C. At this stage, the food sources decreases for microorganisms and the temperature falls, resulting in one more mesophilic stage. In the last stage, the temperature falls to ambient temperature again [Miller 1996, Stofella & Kahn 2001].

About 80 to 90% of the microbial activity during composting is due to bacteria [Haug 1993, Stofella & Kahn 2001]. In composting, species were found belonging to *Bacillus, Pseudomonas, Arthrobacter, Alicaligenes* [Stofella & Kahn 2001], as well as *Staphilococci* [Hassen et al. 2001] in the mesophilic stage. In thermophilic stage, bacteria are predominantly of the *Bacillus sp*., as *B. subtilis, B. stearothermophilic*, and *B. licheniformis*. Above 65°C, compost populations are often reduced to pure cultures of *B. stearothermophilus* [Miller 1996]. The optimum starting temperature for decomposition was found to be 40°C, considering the amount of TOC reduction [Hamoda et al. 1998].

Actinomycetes usually can be observed after five or seven days from the beginning of the composting. They are easily detected because of their grayish appearance in the compost. They are responsible for the "earthy" smell that the compost emits under favorable conditions. *Micromonospora, Streptomyces,* and *Actinomyces* are some species that can be regularly found in composting materials. Actinomycetes play an important role in composting once they have conditions to degrade cellulosic components such as bark, newspaper, and woody stems [Stoffela & Kahn 2001, Wassenaar 2003]. Actinomycetes tend to be common in the later stages of composting. They prefer moist, highly aerobic conditions and a neutral or slightly alkaline pH [Miller 1996].

Fungi are important because they can break down tough debris and organic residues that are too dry (fungi have a lower moisture requirement), acidic (fungi can live in a broad range of pH), or low in nitrogen, enabling bacteria to continue the decomposition process. Fungi are most common in mesophilic and thermophilic stages of composting. Species more common are *Mucor, Aspergillus,* and *Humicola* [Epstein 1997, Miller 1996, Wassenaar 2003].

Ants, beetles, centipedes, green fruit beetle larvae, millipedes, mites, redworms, sowbugs, springtails, and redworms can be found in a compost pile [Wassenaar 2003]. They are important not just for decomposition of the organic matter, but as source of nutrients and biomass to the soil [Epstein 1997].

2.2 *Chemical fundamentals*

Carbon (C) and nitrogen (N) are essential to the composting process. Carbon provides the primary energy source and it is utilized for cellular growth. Nitrogen is also essential to the growth of microorganisms in order to synthesize new cellular material [Diaz et al. 1993, Epstein 1997, Stofella & Kahn 2001]. C/N ratio is a very import parameter and expresses the effect of raw waste quality [Hamoda et al. 1998]. The optimum C/N ratio was found to be in the range of 25 – 30 [Diaz et al. 1993, Epstein 1997, Hamoda et al. 1998, Huang et al. 2004, Stofella & Kahn 2001].

Phosphorus (P) and potassium (K) are also important to the growth of the plants. Substrates such as biosolids, yard debris, and animal manure may have sufficient P, but Municipal Solid Waste (MSW) may not have enough P if it is high in cellulose. Cisteine and methionine - both aminoacids found in protein materials - are the main sources of sulfur (S) in substrates, which in sufficient quantities may generate volatile and odorous compounds (detected by people even at a low-level of concentrations). In well-aerated process, sulfites are oxidized into the sulfates by combining with oxygen in well-aerated zones. However, in anaerobic conditions, volatile organic sulfides and H_2S vaporize into the atmosphere, being responsible for many of the malodor associated with composting. In regard to heavy metals, some countries have established compost quality standards that limit the concentration of heavy metals (arsenic, cadmium, chromium, cobalt, copper, lead, mercury, molybdenum, nickel, and zinc). This refers to the heavy metal concentration of the substrate and the final compost [Stofella & Kahn 2001].

Many organic substances, including MSW, sewage sludge, and other industrial waste are being introduced to composting, which increases the level of heavy metals when compared to the traditional "green" waste compost [Song & Greenway 2005]. However, heavy metals do not seem to be an obstacle to composting. For example, the US Environmental Protection Agency (US-EPA) considers that the levels of trace elements found in MSW compost do not represent a significant risk in terms of human health and impacts to the environment. In addition, the separation of MSW into compostable and non-compostable fractions reduces the level of heavy metals. Another concern about the presence of heavy metals in compost is the possibility of their leaching to groundwater or runoff to surface waters. It has been reported that the leaching of heavy metals increases with application rate of the compost in the soil. However, the concentration of some heavy metals has been reported to be lower than that by the US-EPA drinking water limits [Epstein 1997].

Composting process is relatively insensitive to pH because it has a wide range of microorganisms that work in different pH [Diaz et al. 1993, Stofella & Kahn 2001]. For example, bacteria acidophiles need pH 5 or less for maximal growth; bacteria alkalophiles need a range of pH between 7 and 12; and bacteria neutrophiles need pH about 7.0 [Epstein 1997]. However, the optimum pH generally is considered to be between 6.5 and 8.5. In aerobic composting an oxidation process occurs where O_2 is consumed and CO_2 is produced. Thus, controlling the level of these two gases during the composting process can provide an indication of composting activity. For an efficient composting, an adequate aeration is required, which is based on temperature, free air space, and moisture [Stoffela & Kahn 2001]. Aeration is important to obviously satisfy the O_2 level, to remove water from wet substrates, and to remove the heat generated by organic decomposition in order to control the process temperature [Haug 1993].

2.3 *Physical fundamentals*

Moisture content is an important variable in composting process in order for the bacteria to assimilate their nutrients that could be dissolved in water. Moisture comes from the original moisture of substrates and from the biological oxidation of organic matter. It is lost through evaporation. Diaz et al. [1993] have stated that the microbial activity ceases when the moisture is less than 8% to 15%. It is reported that it may start to occur when the moisture content is about 12% to 15% [Stofella & Kahn 2001]. The desirable moisture content is between 50% and 60% [Epstein 1997, Hamoda et al. 1998, Stofella & Kahn 2001]; although, for domestic waste, the optimum moisture is between 52% and 58% and for food waste it is 60%. Lower moisture levels can make composting facility operators prematurely conclude that their compost process has stabilized. In addition, microbial activity decreases when moisture is below 40%. On the other hand, high moisture levels (above 60%) can block the air passageways, enabling anaerobic conditions with the potential for odor formation. Composting containing materials with structural strength, with a degree of resistance of individual particles to consolidate under compression, (e.g., woodchips, straw, hay (dried grass), rice hulls, and corn stover) can tolerate high moisture of about 75% to 80%. On the other hand, if particles are structurally weak, they are deformed and compressed upon compression, and the volume of interstices is proportionally reduced, which means that it reduces the available space for air and water; so, the permissible water content is lower. Fruit wastes, caning process wastes, sludge, and manures are example of materials that have little or no structural strength. In this case, it is necessary to add a bulking material, which will improve the strength of the compost material. Any material can be added with a high degree of structural strength or even finished compost material (which is usual), or some amorphous material can be added after undergoing a specific process [Diaz et al. 1993].

Particle size affects moisture retention, free air space, and porosity of the compost mixture. Large particle size materials imply more free air space and high porosity. On the other hand, small particle size materials increase the surface contact between O_2 and compost material, increasing the aerobic composting activity. Hamoda et al. [1998] showed that the rate of organic matter decomposition is higher for material of 40 mm particle size due to the fact that the voids between such larger waste particles are bigger than with smaller sizes (5, 10, and 20 mm size), where the oxygen may not access particles easily.

The control of the temperature in composting process is important to maximize the decomposition rate and to inactivate pathogenic organisms [Epstein 1997, Martin 1991, Stofella & Kahn 2001]. For substrates that do not contain human pathogens, a certain desirable temperature is necessary to inactivate plant pathogen or to destroy weed seed. Temperature also affects the moisture content, which affects microbiology activity [Epstein 1997]. The best temperature varies according to the type of substrate that is being used and according to the microorganism population that is desired; for example, there is different optimum temperature to mesophilic bacteria and to thermophilic bacteria [Stoffela & Kahn, 2001].

2.4 *Thermodynamics fundamentals*

The designer of a composting plant needs to understand the microbes involved, reactions they mediate to obtain energy, environmental conditions required for growth and metabolism, and, in certain cases, conditions required to kill organisms such as pathogens [Haug 1993].

The First Law of Thermodynamics is the law of the conservation of energy. The concepts of heat, work, internal energy, and enthalpy are related to the First Law. The Second Law of Thermodynamics resulted from a search to explain the direction in which spontaneous process would occur. The concept of free energy was developed from the First and Second Laws. Free energy gives the useful work, which can be derived from a chemical reaction that occurs under constant pressure and temperature conditions (most microbial reactions occur under such conditions). The water and solid fractions of a composting material can be treated as separate components from a thermodynamic standpoint, which allows calculating the energy balance of a composting process [Haug 1993].

Interesting studies were done in this area very recently. For instance, mass and energy balances of four alternatives strategies were examined for energy recovery from MSW by dedicated waste-to-energy plants generating electricity through a steam cycle. The largest energy savings were achieved by combusting materials recovery without treatment in large scale plants [Consonni et al. 2005]. In another study, energy conservation and carbon dioxide emission reductions due to recycling in Brazil were estimated, given the amount and the composition of waste recycled and the scenario for the energy generation expansion in that country [Pimenteira et al. 2004].

2.5 *Composting*

Composting may be performed in various ways. Currently, the leading concepts are: non-reactor systems (windrows and static pile) and reactor systems (vertical flow, horizontal and inclined flow processes, and nonflow processes).

Windrow is the most common composting method practiced [Diaz et al. 1993, Haug 1993, Stofella & Kahn 2001] and is a potential treatment technique for MSW [Komilis 2006]. Mixed feedstocks are placed into long narrow piles and turned periodically, usually by mechanical equipment.

Height, width, and shape of the windrows vary depending on the nature of the feed material and the type of equipment used for turning [Haug 1993]. Windrow process can be naturally aerated. In this case, the oxygen is supplied primarily by natural ventilation resulting from the buoyancy of hot gases in the windrow system and, to a lesser extent, by gas exchange during turning. Another variation of the windrow process is the one with forced aeration. In this case, oxygen transfer into the windrow is aided by forced or induced aeration from blowers [Haug 1993, Manser & Keeling 1996].

Turning feedstocks aerates the windrow, although not for a long time because microorganisms consume the oxygen within hours [Epstein 1997, Stofella & Kahn, 2001]. Another effect of turning is the loss of water. It can be good, if the substrate has high moisture content. On the other hand, because the turning process makes it easier to add water, it is a good opportunity if the moisture level of the feedstock is low. The frequency of turning is indicated by the ratio of oxygen availability to oxygen demand and it depends on many factors: nature of the material, its structural strength and moisture content, pathogen kill, uniformity of decomposition, and the rapidity of the composition desired by the operator. Turned windrow systems have some limitations. The first is that temperatures lethal to pathogens do not prevail throughout a windrow. Another disadvantage is that the turning procedure can contaminate the sterilized material with nonsterile material in the outer layers of the windrow in which bactericidal temperatures did not develop. Repeated turnings can reduce the pathogens populations to less than affective concentrations. In addition, turning improperly or insufficiently leads to malodors. Reduced frequency, increased space requirement, intensity and frequency of turnings, have also been listed as disadvantages [Diaz et al. 1993].

Static piles may be passively aerated, assisted passive aerated, and aerated. The passively aerated process is based on passive aeration, natural decomposition, to produce compost. It is normally used to slowly decompose cellulostic feedstocks, such as leaves, brush, bark, wood chips, and some agriculture residues. Feedstocks may be combined and mixed to adjust moisture, porosity, density, and/or C/N ratio. After the pile is formed, this is turned with a bucket loader every one to three month, resulting in one or two turnings during the composting cycle [Stoffela & Kahn 2001].

For the static pile process, it is difficult to maintain the aerobic condition; usually, aerobic condition exists only within one to three meters from the pile surface and perhaps along air channels that form within the pile. However, oxygen conditions can be improved with well-mixed feedstocks and with the increasing of porosity.

One of the most common assisted passive aerated methods is the Passively Aerated Windrow System (PAWS). This method involves short windrows with one to three meters height and they are not turned. There are some characteristics usually common for any variation of this method: feedstocks have homogeneous and relatively porous mixture; a delivery system for passive air flow; a base layer of stable absorbent material like straw or compost; and an exterior layer (approximately 150 mm thick) of stable coarse material that retains heat, moisture, odor, and NH_3.

In the aerate static piles method, fans aerate the composting materials. It improves aeration, reduces the processing time, and reduces the potential to produce odors, while providing oxygen, cooling the pile and removing water vapor, carbon dioxide, and other products. There is no intentional turning or agitation; it occurs just when materials are moved [Stofella & Kahn 2001].

Some advantages of this method are that it is simple, requires less area than passively aerated methods and turned windrows, while aerating is better. In addition, it can be enclosed within a building because it is a more compact process and require less space [Stofella & Kahn 2001]. Additionally, static piles are not required to be turned regularly [Manser & Keeling 1996]. This method, however, requires attention due to compaction, short circuiting of air, and inconsistent decomposition within a batch of compost [Stoffela & Kahn 2001]. Moreover this system needs a power supply for the fans, and a control system to alternate the fans between suction and blowing. Another problem is that the air pipe could be in the way of handling equipment inside a plant, interfering in the process [Manser & Keeling 1996].

Within the vertical processes, there are agitated solids bed and packed bed. Agitated solids beds have multiple hearths; solids are agitated during movement down the reactor, with forced aeration. Feeding can be continuous or intermittent and there is some mixing in reactor. A very good example of this type of reactor is the NGK reactor that began operation in 1989 in Japan. In this system, two reactors are provided, each with six cells arranged vertically. The facility composts slightly over two dry tons/day (2,000 kg/day) of lime and ferric conditioned, raw sewage sludge, filtered press cakes. Packed bed (silo reactors) are usually used for composting of sludge cake amended with sawdust and other materials [Haug 1993]. Periodic transfers of solids from the bottom to the top of the reactor occur [Haug 1993, Stofella & Kahn 2001], allowing agitation of the solids. Feedstocks must be mixed before loading. The time that the material remains in the silo ranges from 10 to 30 days, depending on the application [Stofella & Kahn 2001].

Within the horizontal and inclined solids flow, there are the tumbling solids bed, agitated solids bed, and static solids bed. Tumbling solids bed (rotary drums or kilns) have drums usually slightly inclined, rotating slowly (continuously or intermittently), tumbling the material inside. With this movement, the material is mixed, agitated, and moved through the drum or kiln. Feedstocks are feed at the top of the drum and the compost is removed at the opposite side [Stoffela & Kahn 2001]. Agitated solids beds have two variations (agitated bins or open channels). One has cylindrical tanks with a set of screws that allows air to be discharged into composting material. If retention time is less than two or three weeks, the material must be finished in windrows [Diaz et al. 1993]. The other has rectangular bins. Feedstocks are placed into designated cells along the bin length, and they are turned about once a week. They remain in the system for about six days and the material is allowed to mature in windrows over one to two months. This system combines forced aeration with tumbling; the air is forced through the composting mass at least once each day [Diaz et al. 1993, Stofella & Kahn 2001]. For the static solids bed there are two types: tunnel reactor and conveyor type. This system has been applied to a variety of feedstocks, for example: sludge, manure, and MSW fractions. The vessel is essentially a plug flow, tubular reactor or tunnel of rectangular cross section. One design uses a pusher plate with forward and backward movement which is situated at the feed end of the tunnel. Air can be supplied and gases can be removed along the length of the reactor [Haug 1993].

Nonflow reactors (compost boxes) are very simple systems in which materials are loaded in the box reactor and remain there for 7 to 14 days. Aeration is usually controlled and curing is usually conducted in windrows for several months afterwards [Haug 1993].

2.6 *Anaerobic digestion*

Anaerobic digestion has been used for food residuals in Europe for over 30 years [Nichols 2004]. In the U.S., this technology has been growing since 1990 due to increased technical reliability, growing concern of facility owners about environmental quality, increased number of federal and state funds available for cost share, and emergence of new state energy policies [Mattocks & Wilson 2005]. Digestion has been even moved from "unthinkable" to "Best Management Practice" in the West Coast [Mattocks 2004]. This process is used mostly for treatment of municipal sludges and industrial wastes. Some countries such as China and India use the biogas generated for cooking, lighting, and operation of small engines, using the residues as soil amendment [Chynoweth & Pullammanappallil 1996]. Currently, the leading concepts of anaerobic digestion are dry continuous system, dry batch systems, wet continuous systems, and co-digestion [Braber 1995]. In a continuous system, the dry matter varies between 20% and 40% and fresh substrate is added continuously and an equivalent amount is withdrawn once each day or two. In the dry batch system, material is not added or withdrawn from the digester till the digester process has been completed [Diaz et al. 1993]. In addition, each batch lasts for two to three weeks and percolate is recirculated to stimulate mixing and digestion [Braber 1995].

The wet continuous system is subdivided into conventional slurry systems and anaerobic filters. Conventional slurry system usually works with codigestion of animal manure, MSW and other wastes, and a dry matter of about 10%. Anaerobic digesters usually have two- or multi-phases systems. In the first reactor, hydrolysis and acidification of the substrate occur [Braber 1995]. Organisms decompose lipids, cellulose, and protein and generate soluble compounds. Acid bacteria work on theses compounds, producing organic acids. This is known as the acid-former phase [Diaz et al. 1993]. Methane fermentation occurs in the second reactor. Bacteria either work on organic acid producing methane and carbon dioxide or reduce carbon dioxide into methane by using hydrogen or formate produced by other bacteria. The very final products of this stage are methane, carbon dioxide, trace gases, and a stable residue. This is known as the methanogenic phase [Diaz et al. 1993]. About 90% of the facilities in Europe use the one-stage reactor [Vandevivere et al. 2002].

The advantages of wet processes over dry processes are: higher homogeneity of wastes and possibility of separating out contaminants, floating matter, and sediments. On the other hand, the disadvantages are: greater reactor capacity; large material flows to be transported, treated, and heated; higher cost for water supply and dewatering; and slightly lower gas yield since heavy inerts and scum layer need to be removed [Nichols 2004].

The digestion procedures are plugflow, completely mixing, or anaerobic filters. Plugflow is a very simple system: it is lined in an excavated pit with a wall of native materials; the interior of this wall is lined with an impervious material such as a plastic sheet. Suitable provision must be made for capping the pit and collecting and storing the gas. Availability of a suitable lining material may be an issue for some situations. For example, the durability and degree and permanence of impermeability of the plastic sheet are difficult [Diaz et al. 1993]. The mixing can be done either mechanically or by gas injection [Braber 1995]. Mixing is important to achieve an efficient operation of a digester, avoiding sedimentation, and breaking up the scum layer.

Anaerobic digesters may be run at mesophilic or thermophilic temperatures. Mesophilic process has higher operational reliability as the microorganisms are less sensitive to temperature and concentration fluctuations; less energy required for heating up wastes; and higher percentage of methane in biogas. However, the residence time is higher, the volume of gas produced is lower, and the sanitation is not certain [Nichols 2004]. Thermophilic process has been suggested for anaerobic co-digestion of substrates such as mixed municipal and industrial waste [Oleskiewicz & Poggi-Varaldo 1997], anaerobic co-digestion of coffee waste and sewage sludge [Neves et al. 2006], co-digestion of paper mill sludge, biosolids, and MSW [Poggi-Varaldo et al. 1997], and co-digestion of paper mill and MSW [Poggi-Varaldo et al. 1999].

2.7 *Other processes*

For the home composting process, a bin or some type of container is used to keep the composting material within a confined space. The feedstocks that can be used are: garden trimmings, manures, garbage, vegetable trimmings, paper and cardboard, and various absorbent materials. Any decomposable organic material can be used, except human feces, diseased animals, and plant debris heavily dosed with pesticides and other toxic material in general, for reasons of public health [Diaz et al. 1993].

The maximum C/N requirement should be 25:1 to 30:1. For home composting, this ratio can be adjusted considering the relation of "green" debris or garbage to "dry" garden debris. Green debris, e.g., lawn clippings, fresh leaves or plants, green plant stems, roots, flowers are rich in nitrogen. Dry debris, e.g., dried grass (no longer green), matured flowers stalks, branches (excluding leaves), straw, and fall leaves are rich in carbon [Diaz et al. 1993, Hanson 1997].

Another composting process is the vermicomposting, which is an aerated composting system where the redworms process the feedstock, and they excrete vermicasts at the soil surface. Compost worms do best under moist conditions, but are very sensitive to elevated temperatures [Dominguez et al. 1997]. The best temperature for worms is between 13°C and 29°C [Pittaway 2001], although maintaining moderate bed temperatures can significantly increase performance of the process [Frederickson & Howell 2003]. This system can be processed in bed or in windrows, indoor or outdoor.

Vermicomposting supplies mineral balance, improves nutrient availability, and could act as complex-fertilizer granules. In addition, vermicomposting allows a great reduction of pathogenic microorganisms. Vermicomposting may also bring a decrease of bioavailable heavy metals than in the composting process, and there is evidence that the final product may contain hormone like compounds that accelerate plant growth [Dominguez et al. 1997].

3 METHODOLOGICAL PROPOSAL: A MSW TREATMENT FOR MILWAUKEE

Although Milwaukee has recycling plants for newspaper, office paper and cardboard, aluminum and steel/tin cans, glass bottles and jars, and # 1 and 2 plastic containers, and has already plants for composting yard trimmings, in this paper a new methodological proposal is being advocated for Milwaukee (or, any other mid-size cities in USA) that would cover the recycling of the whole amount of MSW generated by the city.

Wisc-DNR reported that Wisconsin generates more than four million tons of MSW per year and has a very successful recycling and waste diversion program. The report also showed that Wisconsin's overall MSW diversion rate is about 40%. Wisconsin's Recycling Law requires everyone in the state whether they are at home, at work, or at a special event to recycle newspaper, office paper and cardboard, aluminum and steel/tin cans, glass bottles and jars, and # 1 and 2 plastic containers. [WDNR 2003].

The City of Milwaukee has approximately 940,000 habitants [DHFS 2004], which is about 17% of the population of Wisconsin, according to the Census 2004. Therefore, the MSW generation from Milwaukee can be extrapolated, considering 17% of the total MSW generated by Wisconsin. It means that Milwaukee produces about 2,000 metric tons/day of MSW. From this total amount, about 18% consists of organics (yard waste, food, diapers, animal waste/kitty litter, and bottom fines/dirt). In addition, the DNR report showed that food waste is a material found in sufficient quantity (10%) to offer significant opportunities for increased diversion for composting.

A flow chart for the proposed MSW treatment plant is shown in Figure 1. The methodology of recycling MSW consists of a combination of various unit operations. The proposed unit operations in this paper are generally known in the world of recycling. The design of the cited unitary operations is simple most of the time, but extremely important. The key to success as proposed in this paper is the selection of the better combination of the unit operations in this process in order to obtain the best results for recycling matter and energy in this complex process.

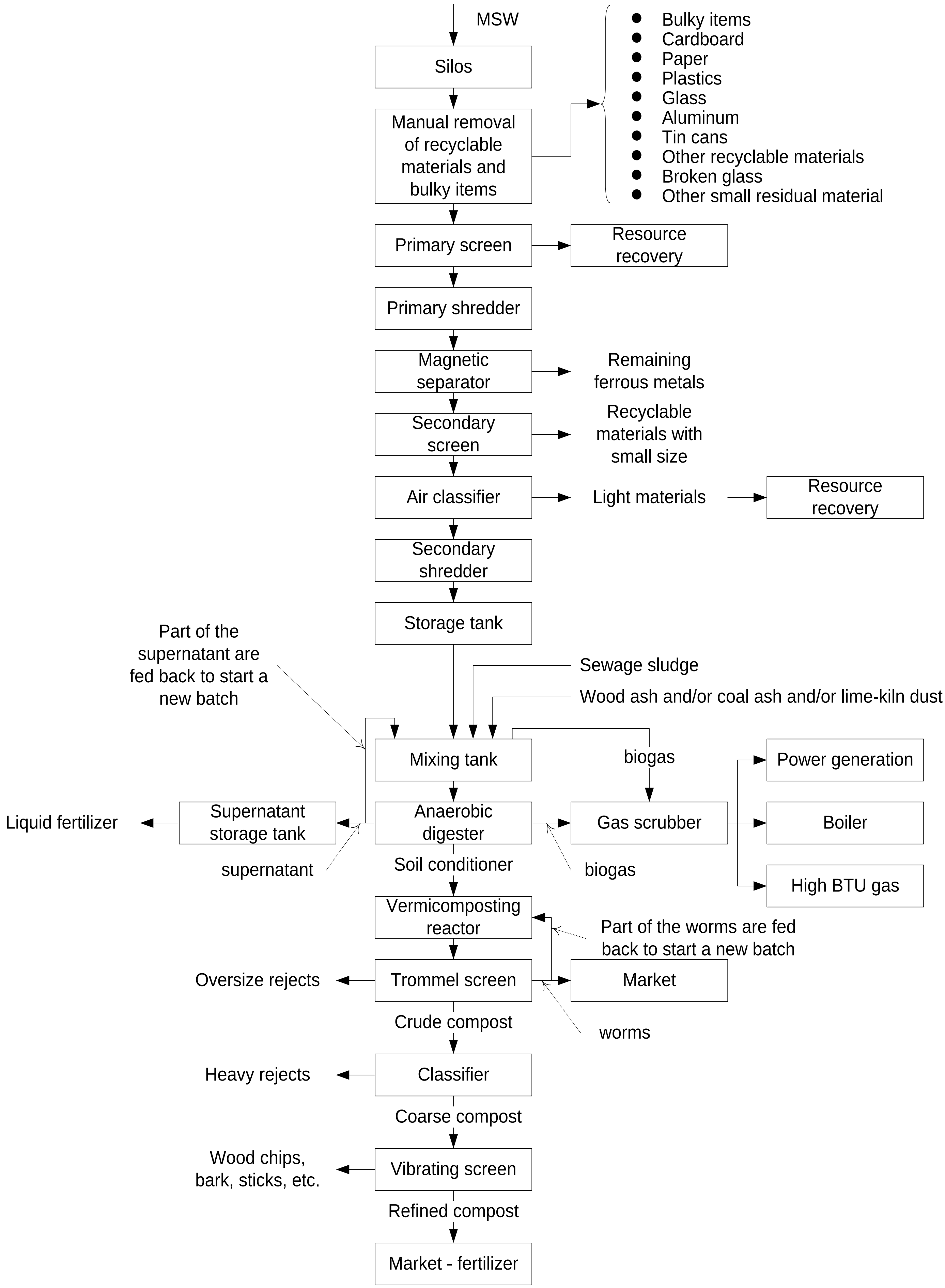

Figure1. Flow chart for the proposed MSW treatment plant.

The methodological proposal involve three main steps: (1) picking up station for removing bulky material and recyclable material; (2) anaerobic digestion, and (3) vermicomposting.

Considering the proposed plant, a city the size of City of Milwaukee would need about 70 garbage trucks managing two routes a day, assuming that a garbage truck has the capacity of 15 metric tons.

In order for each silo to receive one truck load, and considering the average density of mixed MSW as 0.44 metric ton/m^3 (26 lb/ft^3) in the garbage-truck and 0.24 metric ton/m^3 (14.8 lb/ft^3) after dumping from garbage-truck [Diaz et al. 1993], it will be necessary to have the silo with the capacity of 65 m^3.

In addition, considering that the new composting plant would work 24 hours a day, seven days a week, it means that the plant is expected to process about 85 metric tons/hour.

Furthermore, a conveyor belt is proposed under each silo, and the unloading of the silo controls the velocity of each conveyor belt. It means that it would not be necessary to have a valve in the exit of the silo, which means a reduction on the cost of the process and one less variable in the process.

It is suggested that the silo has one meter height extension on their upper part. The objective is to avoid MSW falling outside the silo during the unloading of the garbage-truck. It is suggested that each silo has an angle of 66°, since it avoids build up in silo walls [ASTEC 2004].

3.1 *Processing plant*

The plant would have six conveyor belts, one for each of the six silos.

The volume (V) of the silo is one m^3, considering dimensions of 0.5 m x 0.5 m x 4 m. The mass (m) of the material of the silo is 0.24 metric tons.

Considering that

$$v = QL/m \qquad (1)$$

where v is velocity of the conveyor belt, Q is flow of the material of the silo, L is length of the silo and m is mass of the material of the silo, the velocity of each conveyor belt should be 24 m/min. As 24 m/min is so fast, it is suggested to have 2 silos and two conveyor belts (one for each silo) in the plant, in order to reduce the velocity of each conveyor belt to 12 m/min.

In regard to the sorting station, it is known that nowadays there are a considerable number of studies against the sorting of all material only manually, since it increases costs with employees and reduces the quality of the feedstock to composting and the quality itself of the recyclable material. For example, it is recommended to have screens or a series of screens in the beginning of the process to separate paper from the other materials, since paper and paperboard correspond to major products to be recyclable. In addition, there are machines that can sort the materials automatically, guaranteeing the quality of sorting. However, for the recycling process of MSW, it was chosen to work with a very common situation such as hand picking station. In addition, it is known that Milwaukee has curbside residential recyclables collection program, in which non-organic materials, such as glass, metals, and newspaper are removed from the MSW feedstock. Therefore, in this process, the MSW generated by the City of Milwaukee can be readily and efficiently sorted at the plant.

The number of employees in the new composting plant (in the MSW recycling area, which is the area that most demand employees) is estimated from some data from other MSW recycling plants. The Del Norte Regional Recycling and Transfer Station in the City of Oxnard, California process about 1,300 metric tons of waste and recyclable material a day and have nearly 100 employees. The Columbia County, Wisc., solid waste operation process 100 tons of waste and recyclable material a day and have 16 employees [Tilton 2000] Therefore, in the California plant the productivity is 13 metric tons/employee/day and in the Wisconsin plant is 6.25 metric tons/employee/day.

Therefore, it is estimated that the proposed plant will have a productivity of about 10 metric tons/employee/day, which is the average of the productivity of the two plants cited above. This is a reference number since the plants work 24 hours a day and it is not exactly known what the productivity per employee would be. Therefore, it is estimated that the proposed plant will need about 200 employees.

Considering three work shift and considering that each work shift has the same demand, each work shift will about 70 employees. It means that approximately 35 employees per sorting line would be needed. The number of employees per each sorting line might be too high because they were based on the number of employees reported for the two plants already referred (California and Wisconsin). It is not clear the exact number of employees working specifically on sorting line. However, probably the plant may still need this number of employees to work in the new proposed composting plant, considering all departments, including the MSW recycling department.

After each sorting line of the proposed plant, there would be two screens: the primary screen and the secondary screen.

It is specified that the primary screen would have 127 mm (5") openings [Hecht 1983] with capacity of 50 metric tons/h; the secondary screen would have 13 mm (½ inch) openings [Hecht 1983] with capacity of 30 metric tons/h.

3.2 *Composting plant features*

To harvest worms it is indicated 6 mm (¼ inch) screen [Codner 2000] be used for the first pass, with capacity of 0.79 metric tons/h.

Experience shows that for a city the size of City of Milwaukee, primary hammermill should have a capacity of 50 metric tons/h and the secondary should have a capacity of 25 metric tons/h. The magnetic separator should have a capacity to process 32 metric tons feedstock per hour, separating 0.58 metric tons/h of ferrous material. The air classifier should have a capacity to process 30 metric tons/h.

The density of food waste ranges between 0.35 metric tons/m^3 to 0.40 metric tons/m^3 [Hecht 1983], and yard waste shredded and mixed ranges between 0.14 metric tons/m^3 and 0.19 metric tons/m^3 [Hickman Jr. 1999]. The density of the water/moisture is one metric ton/m^3. In addition, if the mass of feedstock is 563 metric tons, of which 47% is food waste, 20% yard waste, and 33% moisture, then the minimum volume of the storage tank should be 2,700 m^3 (considering a safety factor of 1.5), since

$$d = m / V \qquad (2)$$

where d is density, m is mass of the feedstock, and V is the volume of the feedstock.

The proposed composting plant should have seven storage tanks of capacity of 2,700 m^3 each, considering that each tank receives the daily demand of 1,754 m^3 and considering that the residence time of feedstock in the next step – mixing tank – is seven days.

The proposed compost plant should have seven mixing tanks at 37ºC (mesophilic temperature), since the residence time in each tank is 7 days. Therefore, it will have one mixing tank to receive the feedstock from each storage tank. The volume in each of these tanks should be higher than the storage tank, since in this step other materials are added as sewage sludge, wood ash, coal ash, and/or lime kiln dust. The quantity of these materials is not yet determined, since this subject requires additional work and empirical proof. The volume of each mixing tank should be 3,500 m^3, since a safety factor of 2.0 is more appropriate to estimate the volume of each of the seven mixing tanks.

In the mixing tank biogas is also generated. However, in order to calculate the production of biogas, it is assumed that the total production would come from anaerobic digester only.

3.3 *Anaerobic digester*

Considering that the recommended retention for Rotaller model anaerobic digester tanks time is between 2 to 15 days [RISE-AT 1998], the proposed composting plant should have anaerobic digesters with 7 days of retention time at 55ºC or higher. It is estimated that the volume of an anaerobic digester is three times higher than a mixing tank, since the generation of gas is higher too, based on data from an anaerobic digester plant from Anyang City, Korea, which process MSW [RISE-AT 1998]. Then, the volume of each anaerobic digester should be approximately 10,500 m^3. However, this is a large volume, the proposed plant would have two anaerobic digester tanks with 5,000 m^3 for each mixing tank. The total amount of anaerobic tanks required is 15.

Usually the volume of biogas produced varies between 0.6 m^3/kg solids to 0.9 m^3/kg solids [Hickman Jr. 1999]. In addition, considering that the solids entering in the anaerobic digester are 450 metric tons of feedstock (it is being considered just the mass of BSW), and that usually between 40% and 60% of the organic matter present is converted to biogas [European Commission 2004], the volume of biogas generated in the proposed plant is 135,000 m^3, since:

(225,000 kg BSW) (0.6 m^3/kg) = 135,000 m^3 biogas/day, considering 50% of the BSW.

Considering that the calorific value of biogas is 20.5 MJ/m^3 [Hickman Jr. 1999], and the lowest reported generation rate is 0.6 m^3/kg, then the resulting potential calorific value of the waste is 12.3 MJ/kg.

Therefore the power generation of the proposed plant is 768,750 kWh, since:

(12.3 MJ/kg)(225,000 kg BSW) = 2,767,500 MJ/day = 768,750 kWh/day

However, assuming that the efficiency of the generator is 25% [European Commission 2004]; so, about 190,000 kWh is produced per day.

In the proposed composting plant, part of the biogas would be stored in spherical tanks of 5,000 m^3, to satisfy the demand of energy and steam of the composting plant. Remaining may be sold to an electricity power company by the City of Milwaukee.

It is considered that 50% of mass of the feedstock would be used to generate biogas and the other 50% would generate compost and liquid fertilizer. Therefore, the proposed composting plant will generate about nine metric tons of compost per day and 190 metric tons of liquid fertilizer.

In the Anyang City, Korea, the anaerobic digester plant produces 230 m^3 of biogas per day, 100 kg compost, and two metric tons of liquid fertilizer from three metric tons of food waste [RISE-AT 1998].

If three metric tons of waste generates 230 m^3 biogas, the 563 metric tons of waste from the proposed Milwaukee plant would generate 43,000 m^3 biogas, if the process was exactly the same. However, it would probably generate 135,000 m^3, because the feedstock has different composition. Therefore, in the Korean plant the generated volume is proportional to only 9% of the feedstock of the proposed Milwaukee plant.

In order to estimate the generation for the proposed plant, the proportion of the generation of each product (compost, biogas, and liquid fertilizer) was calculated assuming that in the proposed plant 50% feedstock would be used to generate biogas.

3.4 *Vermicomposting*

It is necessary to have 45 kg of worms to process 34 kg of feedstock. Therefore, the proposed plant would require 6.8 tons of worms.

It is reported that the residence time in a vermicomposting system is about 30 days if this is the only composting step in the process [Dominguez et al. 2000]. However, considering that when the product leaves the anaerobic digester, it is already a soil conditioner [RISE-AT 1998], the vermicomposting reactor will just refine the compost. Therefore, it is estimated that only 10 days of residence time should be enough.

Because Milwaukee has a cold winter, reaching temperatures of about minus 20°C ± 5 °C, it is necessary to insulate the vermicomposting tanks with polyurethane, in order to keep the temperature of the tank between 13°C [Holmstrup 2004] and 29 °C [Holmstrup 2004, Pittaway 2001], which is the best temperature for worms. In addition, the reactors should be preferably in a building (indoor system) insulated too.

The supernatant storage tank should store at least the production of one day. Therefore, the storage tank should have the capacity of about 200 metric tons of liquid fertilizer. Considering the density of liquid fertilizer as the density of water (1 metric ton/m^3), the minimum volume of the tank is 200 m^3. This is assuming that the part of the liquid fertilizer be fed back to the mixing tank.

This proposed process would allow obtaining a faster composting process since the residence time in the mixing tank and in the anaerobic digester is seven days, and, therefore, the total time is 14 days. At this point, the resulting product is a soil conditioner. It means that probably only 10 days of residence in the vermicomposting reactor (instead of the usual 30 days) will generate the finished compost.

4 CONCLUDING REMARKS

Composting and anaerobic digestion are multivariable processes, based on microbiological, chemical, physical, and thermodynamics fundamentals. They have several variations; they may be operated in open or closed reactors. They represent intelligent options for processing MSW, converting organic matter into soil amendment, managing dwindling landfill space, and be a potential source of renewable energy.

As a solution to efficiently treat MSW and obtain compost and energy at the same time, it is proposed to have a plant with anaerobic digester followed by vermicomposting. The compost obtained by anaerobic digester has the same quality of the compost obtained by aerobic digester, with the advantage that the process generates liquid fertilizer (which can be marketed as a soil conditioner) and biogas (which can be used to provide energy and steam to the plant and also sell the gas).

A vermicomposting reactor would follow an anaerobic digester reactor. It is probable that it is not necessary to blend the compost with other minerals to complement its profile. In addition, the combination of these two unit operations would allow reducing significantly the total process time.

It is proposed to co-compost MSW, which is a major concern worldwide, with sewage sludge, adding wood ash, fly ash, lime-kiln dust, and /or limestone quarry dust to reduce the generation of organic sulfur from the anaerobic digester.

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