Water Requirements in an Aerobic Bioreactor Landfill Environment

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ABSTRACT: In an aerobic bioreactor landfill environment, water and air are added or injected into the waste mass to sustain aerobic and biotic respiration reactions. This paper provides an overview of step-by-step calculations, based on the stoichiometry of biotic respiration reactions, to estimate values for water inputs/production and consumption/uptake for an aerobic bioreactor landfill project in China located in a semi-arid climate. The Hydrologic Evaluation of Landfill Performance (HELP) Model is also used to estimate the amount of water infiltrated through a final cover system in order to estimate the net water inputs or production within the system.

Water requirements in an aerobic bioreactor landfill environment can be estimated in two phases: (1) the initial amount of water required to increase the waste moisture content to an operational and safe range of at least 40 percent and (2) the amount of water required for hydrolysis and biologically mediated oxidation reactions to sustain microbial activities during operations.

In Phase 1 calculations, the initial waste moisture content needs to be established or field verified. The difference between the targeted waste moisture content and the initial waste moisture content gives the required water that needs to be introduced into the landfill prior to operating the aerobic bioreactor system.

In Phase 2 calculations, the water inputs/production for the subject site is estimated from (1) the precipitation and run-on infiltrating through the final cover over a targeted duration, (2) leachate recirculation (if any), and (3) liquids produced by biologically mediated reactions. The water consumption/uptake is estimated from either the water removal caused by vaporization (carried via advection with the exhaust air stream) or by hydrolysis/biologically mediated reactions. The water removal caused by vaporization is estimated using data collected from previous aerobic projects in the United States but is also estimated based on the subject site conditions in China. The net water balance between the water inputs/production and the water consumption/uptake can be either a deficit or surplus of water within the aerobic system over the targeted duration of operations.

A case study is presented to illustrate the methodology used in estimating the water requirements to operate an aerobic bioreactor landfill remediation project.

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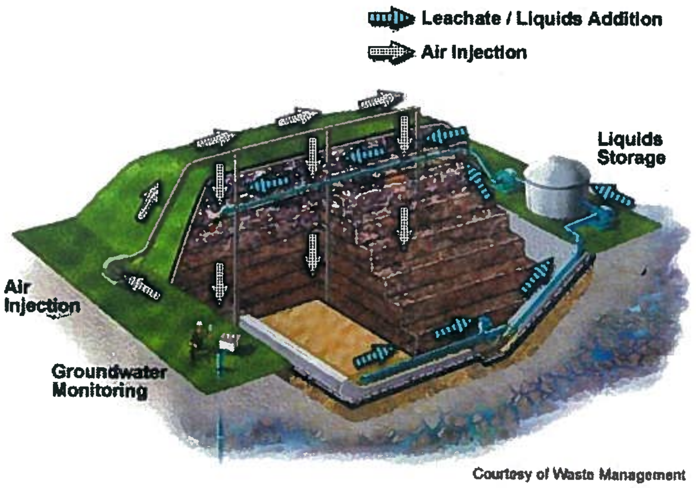
INTRODUCTION

As early as the late 1990s, aerobic biodegradation processes (aerobic bioreactor) were developed using the landfill itself as a treatment bed (similar to a large closed vessel), to promote a more rapid and effective treatment of waste and leachate. This biodegradation process involves adding air, moisture, and other nutrients uniformly to the waste mass on a large scale similar to waste composting, but without mixing or windrowing of the waste. In effect, the landfill cell acts as a "bound unit" consisting of a landfill liner, sideslopes, and cover to manage and control leachate, landfill gas (LFG), and other factors associated with aerobic waste composting, such as waste moisture content and temperature. Other benefits include reducing concentrations of certain organic compounds typically found in wastewater and leachate (Read, 2001)

Some of the assumptions in managing landfills using traditional anaerobic technology are that waste degradation is slow and that methane gas will always be produced in concentrations greater than 50 percent by volume of the total LFG gases (Doorn, 1995). Active aerobic biodegradation processes (such as composting), however, have demonstrated that the biodegradable portion of municipal solid waste (MSW) can be stabilized in a significantly shorter time frame (as compared to anaerobic conditions) and that (due to the increased availability of injected oxygen), methane production can be greatly reduced (Stessel, 1992). Further, by recirculating the leachate back into the waste (assuming that there is a leachate collection system at the bottom of the landfill) and, at the same time, injecting air into the waste, the facultative and respiring bacteria inherent to the waste convert the biodegradable mass of the waste and other organic compounds to mostly carbon dioxide and water (instead of methane), with a safe, degraded humus remaining (Hazen, 2000). This process is generally depicted in Figure 1. Since aerobic biodegradation also treats liquids by reducing contaminant concentrations, the need for subsequent landfill leachate treatment is reduced.

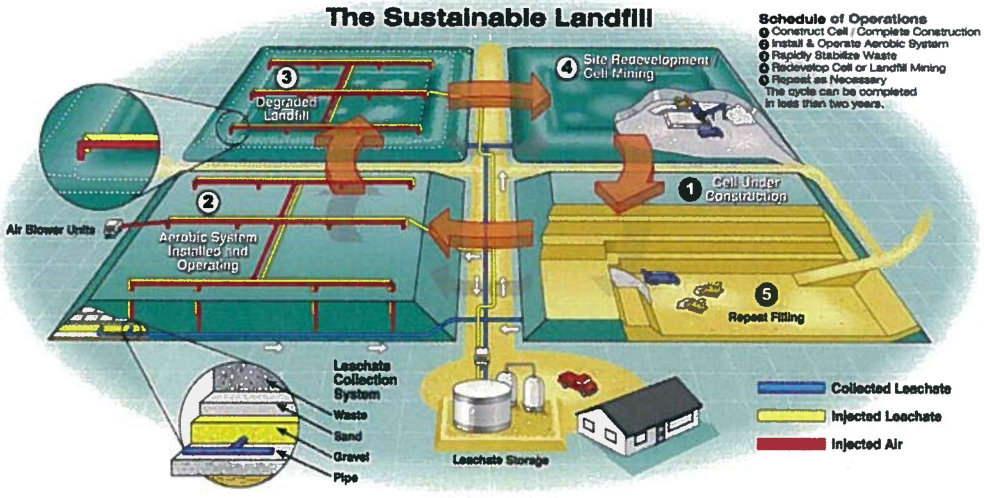


Source: http://www. epa.gov/epaoswer/non-hw/muncpl/landfill/aerobic.htm

Figure 1: Schematic of Aerobic Landfill in RCRA Subtitle D Landfill

Aerobic biodegradation is an important consideration for waste facility owners who want to effectively respond to society's demands for greener and more sustainable landfill operations. The debate on different waste management practices has become an issue of utmost importance as human activities have overloaded the assimilative capacity of the biosphere. Recent laws on solid waste management recommend an increase in material recycling and energy recovery, and only foresees landfill disposal for inert materials and residues from recovery and recycling. However, a correct waste management policy should be based on the principles of sustainable development, according to which our refuse is not simply regarded as something to eliminate but rather as a potential resource. This requires the creation of an integrated waste management plan (IWMP) that makes full use of all available technologies.

For example, the idea of a "sustainable landfill" is an IWMP which consists of five-phase activities: (1) landfilling/reusing of a cell, (2) installing and operating an aerobic/anaerobic biodegradation system, (3) degrading landfill, (4) landfill cell mining, and (5) landfill cell construction/reuse. An idealized sustainable landfill is illustrated in Figure 2 (Hudgins, 2007). The understanding of water balance as part of such a system would be critical, if implemented.



Source: LG Aerobic Solutions. LLC

Figure 2: Schematic of a Sustainable Landfill

LIQUID BALANCE ESTIMATIONS

Water production and consumption data have been collected from several aerobic landfill projects for over a decade. Yet, variability in waste characterization, heterogeneity, and cell construction has provided data that present consistent findings. More research is still needed in these areas; however, it is possible to hypothesize the production and consumption of liquids in an aerobic landfill by a review of the basic stoichiometry of composting and related mechanical/thermal processes and comparing the results to those obtained in the field. This paper presents the methodology of estimating quantitatively the water inputs/production and water consumption/uptakes in aerobic bioreactor landfill environment.

AEROBIC LANDFILL PROCESS

The aerobic landfill process is essentially a biological one that involves the growth and control of microorganisms. The rate of the aerobic process, like the rate of composting, can be affected by many factors. Although composting and aerobic landfilling are conducted using different engineering solutions (windrows versus air injection), the ability to provide oxygen, water, and nutrients to a unit volume of waste (organics) is quite similar. Therefore, in most cases, large scale composting can serve as a surrogate for aerobic landfilling.

Presented are general descriptions of the aerobic process. The four key considerations are (1) nutrient balance, (2) moisture content, (3) temperature, and (4) aeration. There are many other factors that need to be considered in effective aerobic landfill operation. Microorganisms need nutrients, primarily carbon and nitrogen, for both energy and growth. However, the most important factor is moisture content. This can be monitored using a moisture balance. MSW (because of high carbon content) may take years to compost if insufficient water is not present. The organic fraction of MSW decomposes to produce a good finished product if moisture is adequate and if the pile is aerated sufficiently to ensure a good supply of oxygen.

Aerobic landfill systems rely on the natural process of composting; however, instead of windrow turning, the provision of oxygen to the waste mass, as well as the application of moisture is accomplished via wells installed into the waste. This addition of air and the recirculation of liquid or leachate provide a combination of oxygen, moisture, and nutrients to the indigenous, respiring microorganisms to promote a high growth rate and metabolic activity. In each case, a reliable, well-engineered, flexible system for adding air and leachate is designed to treat the waste *in-situ.* Using readily available materials and equipment typically used in LFG collection systems, aerobic landfill systems can be integrated into the existing landfill infrastructure.

Based on the work presented in U.S. Patent Number, 5,888,022 "Method and system for treating bio-degradable waste material through aerobic degradation" the moisture content in the landfill is increased from approximately 40% to about 70% while oxygen is injected into the landfill to drive and maintain primarily aerobic degradation of the waste material. The temperature in the landfill is increased to substantially eliminate pathogens from the waste material. The temperature in the landfill is controlled within a range of approximately 130 to 150 degrees F to sustain the primarily aerobic degradation. Oxygen content, moisture content, and temperature in the landfill are monitored and varied to maintain aerobic degradation in the landfill.

Aerobic conditions are balanced by adjusting the flow of liquids and air that are injected into the waste mass in order to keep the waste moist and aerated, and to keep landfill gases (CO_2, CH_4, and O_2) and waste mass temperatures within safe, optimal ranges. The goal is to operate the aerobic remediation system to reduce the production of methane, a greenhouse gas (GHG), degrade much of the wastes' organic matter faster than can be achieved via anaerobic decomposition (common to most landfills), and stabilize the landfill to the point whereby redevelopment can occur on a more stable foundation.

Stoichiometry

Aerobic degradation of waste can be represented by the following reaction (Tchobanoglous, 1993):

$$C_aH_bO_cN_d + (4a+b-2c-3d)/4\ O_2 \rightarrow aCO_2 + dNH_3 + (b-3d)/2\ H_2O \qquad (1)$$

Where:

$C_aH_bO_cN_d$ = molar composition of the organic waste

= $C_{35}H_{73}O_{30}N$

The use of Equation (1) provides a conservative estimate of the oxygen required as bioconversion to end products is less than 100 percent. This equation was used to determine water production and demand, oxygen uptake, and nitrogen requirements, as presented below.

The primary goal of the aerobic landfill process is to achieve optimum waste stabilization through aerobic degradation (Hudgins, 2007). This is defined in terms of a stabilized organic matter, decreased concentrations of leachate contaminants, reduced methane production, and waste mass subsidence. Laboratory and field analyses provide the data needed to determine the system's effectiveness on the leachate. Direct measurements of landfill gases are used to determine the amounts of methane and non-methane organic compound (NMOC) production. The subsidence of the landfill waste mass is monitored by physical survey. Although, the biodegradation rate of this process can be determined in various manners, for most applications, the biodegradation rate is determined based on oxygen uptake rates, reduction in volatile solids (VS) material, and waste mass temperature measurements. Upon stabilization, the waste can be excavated to examine the degree of aerobic decomposition.

In many cases, the degree of bioconversion obtainable can be estimated by calculating the biodegradable fraction of the solid waste using Equation (2) (Chandler, 1980):

$$BF = 0.83 - 0.028\ LC \qquad (2)$$

where BF =biodegradable solids fraction expressed on a volatile solids (VS) basis
0.83 = empirical constant
0.028 = empirical constant
LC = lignin content of VS as a percent of dry weight

Biodegradability fractions range from 0.22 for newsprint up to 0.82 for food wastes.

Targeted Moisture Content

Maximum moisture content for satisfactory aerobic operation varies with the waste materials present. If the waste materials contain considerable amounts of strong fibrous material, the maximum moisture content can be much greater without destroying the structural qualities or causing the material to become soggy, compact, and unable to contain enough air in the interstices. If the waste material has little structural strength when wetted, or if it is granular, like ash and soil, it may be difficult to maintain aerobic conditions.

The targeted moisture content of MSW should typically be at least 40 percent, but may be in a range between 40 to 70 percent. This is important because as the target moisture content is exceeded, the structural strength of the organic matter deteriorates, oxygen movement is inhibited, and the process tends to become anaerobic. As the moisture content decreases below 50 percent, the rate of decomposition decreases rapidly (Hansen, 1995). If the moisture content falls much below 40%, many of the organisms will cease to function. Moisture content above 70% may cause the waste to go anaerobic, thereby producing foul odors.

CASE STUDY CALCULATION -- CHINA

The goal of this case study sample calculation is to theoretically derive, based on the stoichiometry of biotic respiration reactions, values for water inputs/production and consumption/uptake. Also, a water balance within the bioreactor system is performed to estimate the amount of extraneous water that should be added to the system throughout the operation.

The approach to water application is a two-phased approach. The first phase brings the waste moisture content up to the required range to sustain microbial viability. The second phase involves maintaining the moisture range, even under the drying conditions of forced air entry.

Presented below is a sample calculation of water requirements at an aerobic bioreactor landfill remediation project in China.

Assumptions

Based on site information and from data collected during site inspections, performance modeling was based on the following field data (2007) and assumptions:

- Landfill subject area: 1.4 million square meters (14 ha or 35 acres) (measured);
- Volume of waste: 2 million cubic meters; (measured)
- Waste density: 600 lbs/cy (350 kg/m^3); (estimated)
- In-place waste moisture content: 27.66 %, (measured)
- Volatile Solids (VS): 22% of Total Solids (measured);
- Biodegradable Fraction of Volatile Solids: 60% of VS (measured);
- 15% of the waste is Carbon (assumed);
- Preferred ratio of Carbon to Nitrogen: 25 to 1;
- No daily cover used (reported);
- Target treatment period for all VS: 2 years.(estimate based on stoichiometry)

Assuming a waste density of 600 pounds per cubic yard (no waste compactors used), the discarded weight of total solids (including moisture) inside the subject waste mass (w) is estimated to be 7.85 E+05 tons (1.57 E+09 lbs or 7.1 E+08 kg). This maximum value for waste weight is used, rather than the adjusted value to account for the anaerobically biodegraded waste fraction, to assess the maximum water requirements.

Phase 1 - Initial Amount of Water Required prior to operations

Based on the waste sample collection in 2007, the average reported in-place moisture content (mc) of the waste in the mound is 27.66% (by wet weight). This translates to an estimated dry weight, d, of:

$$mc = 100 \times (w - d)/w \tag{3}$$

$$27.66\% = 100 \times [(7.85\text{ E+05 tons} - d)/7.85\text{ E+05 tons}]$$

Solving for d, d = 5.68 E+5 dry tons, or 1.14 E+09 lbs (5.16 E+08 kg)

As observed at previous aerobic remediation projects, the estimated minimum moisture content (mc) required is about 40% (average by wet weight, w). Therefore, if we assume that 40% wet weight is our optimum goal for peak aerobic/composting performance, the volume of additional water required to bring the waste from completely dry weight up to 40% wet weight is:

Solving for w, w = 9.47 E+05 tons of wet solid waste, or 1.89 E+9 lbs (8.61 E+8 kg)

Therefore, the additional water required to bring the moisture content from 27.66%, its current moisture content, to 40% wet weight is 3.88 E+07 gallons, or 1.48 E+08 liters.

Phase 2 - Water Required To Sustain Microbial Activity

Assumptions used in Phase 2 calculation are as follow:

- Moisture input projections assume an even distribution of waste, which in reality is not going to occur. Certain areas of the waste mound will require additional moisture injection, while others must be curtailed.

- Cellulose/hemicelluloses (carbohydrates) are the primary biodegradable carbon source in solid wastes. If we use 63% (CEC, 2003) of the total dry weight as cellulose/hemi-cellulose (0.63 x 1.14 E+09 lbs dry weight), then 7.18 E+08 lbs is in the form as cellulose/hemi-cellulose. Yet, as part of the theoretical calculation to determine nitrogen availability based on C:N ratios, less carbon was estimated, From previous projects, waste sample analysis indicated that 15 percent of the waste (wet weight) was carbon. Thus, using this relationship, it is assumed there are 2.36 E+08 lbs (0.15 x 1.57 E+09 lbs) of carbon present.

- To simplify the carbon calculations, only cellulose/hemi-cellulose reactions were considered, and the associated water production/consumption, for estimation of the water balance, assuming the more conservative weight of 2.36 E+08 lbs of carbon.

- Using this value and the preferred C:N ratio of 25:1, the nitrogen requirement was estimated to be 9.44 E+06 lbs. As it was calculated that there are 2.1 E+07 lbs of nitrogen available, based on molar weights, there appears to be an adequate amount of nitrogen available from this theoretical calculation[5]. For these calculations, it was assumed that nitrogen requirements do not effect water production or demand.

- To simplify the overall calculations and to arrive at maximum anticipated inflow requirements, an assumption was made that vaporized moisture does not condense within the waste mass. However, in field observations, there are liquids present because of factors that may include the percentage of treatment effectiveness resulting, variability of waste, leakage through cover, and presence of groundwater.

Based on stoichiometry ratios for water consumption and production relative to carbon, the following totals were derived from Equation 1:

$$C_{35}H_{73}O_{30}N + 37.5O_2 = 35\ CO_2 + 35H_2O + NH_3 \qquad (4)$$

Also, the following assumptions were made:

- Composition of organic fraction (including water) of a composite waste sample is $C_{35}H_{73}O_{30}N$ with 987 lbs. per mole;
- Composted products have total molar weight of 1200 lbs. per mole
- Volatile solids (VS) = 22% of total dry solids;
- Total dry solids = 1.14 E+09 lbs;
- Total carbon = 2.36 E+08 lbs
- Biodegradable fraction of VS = 60% of VS;

Water Consumption (x_b) Via Biotic Reactions

Given that cellulose/ hemi-cellulose (carbohydrates) reactions utilize 4 moles of water per 6 moles of carbon consumed, then the water consumption via hydrolysis/biologically "mediated" oxidation reactions can be calculated as follow:

- [5] This relationship assumes all of the nitrogen is released (100 % breakdown of organic compounds) and is available for assimilative use by the microorganisms. However, some of the nitrogen may not be readily available due to the presence of any recalcitrant organic species and the subsequent limits to nitrogen release from these compounds. Also, nitrogen use for assimilative purposes by certain species of microbes may be limited depending on the oxidation state of nitrogen. As a result, based on theoretical and empirical data, there may be no need for nitrogen addition to the aerated bioreactor system. Therefore, water estimates do not consider the effects of nitrogen.

$$\frac{(4 \times 18)\ \text{lbs/mole}\ (H_20)}{(6 \times 12)\ \text{lbs/mole (Carbon)}} = \frac{x_b\ \text{lbs}\ H_20}{2.36\ \text{E+08 lbs. of Carbon}} \tag{5}$$

x_b = 2.36 E+08 lbs of water/8.34 lbs per gallon
= 2.83 E+07 gallons of water **consumed**, or 1.08 E+08 liters

Water Production (x_h) Via Biotic Reactions

From the biotic stoichiometry of oxygen requirements, 12.5 moles of water are produced for every mole of organic compound oxidized. Each mole of organic compound found through analysis will contain 12.5 moles of carbon. Therefore, the water production via hydrolysis/biologically "mediated" oxidation reactions can be calculated as follow:

$$\frac{(12.5 \times 18)\ \text{lbs/mole}\ (H_20)}{(12.5 \times 12)\ \text{lbs/mole (Carbon)}} = \frac{x_h\ \text{lbs}\ H_20}{2.36\ \text{E+08 lbs. of Carbon}} \tag{6}$$

x_h = 3.54 E+08 lbs water / 8.34 lbs per gallon
= 4.24 E+07 gallons of water **produced**, or 1.61 E+08 liters

Water Removal Due to Vaporization

The following assumptions were made:

- The weight of air is approximately 0.071 lbs per cubic ft.;
- The average inflow air temperature is 100 deg F (37.8 *C),* of which approximately 21% by mass is O_2. Moisture in the inflow air is ignored to simplify the calculation but it can be important for some arid sites; and,
- The volume of water vaporized and carried via advection with the exhaust air stream is approximately 0.0019 gallons per minute of water/cubic foot per min (scfm) airflow. (CEC, 2003)

Based on Equation 4, a theoretical oxygen demand is calculated to be 1.22 lbs O_2 for each lb of organics to convert. Therefore, since there is a total of 2.36 E+08 1bs of biodegradable organics to convert, 1.22 x 2.36 E+08 lbs or 2.88 E+08 lbs of O_2 is needed to be delivered to the system. This is then converted to 1.95 E+10 cubic feet at 100% conversion efficiency of O_2 or approximately 18,550 scfm for two years continuous operation. At 50% conversion efficiency of O_2, the air required would be 37,100 scfm for two years continuous operation.

Based on the above oxygen requirements at 50% conversion efficiency of O_2, the amount of water vapor removed from the system, assuming the vapor is allowed to fully vent to the atmosphere through the vent wells or be extracted via vacuum is:

37,100 scfm x (0.0019 gpm water/scfm airflow) = 70.5 gpm water content within air flow

The total volume of water removed is:

70.5 gpm x 60min/hr x 24hr/day x 365 days/yr x 2 years = 7.41 E+07 gallons
= 2.94 E+09 liters

Water Input Due To Infiltration of Precipitation

Using "The Hydraulic Evaluation of Landfill Performance" (HELP) model developed by the U.S. Environmental Protection Agency, the water input because of infiltration of precipitation was calculated to be a very small amount when compared to other volume. The small volume was caused by the fact that there is very little rainfall at this arid site and this site is capped with a low permeability clay cover with a hydraulic conductivity of approximately less than $5x10^{-6}$ cm/sec. Any rainfall or snow melt is presumed to flow through surface water controls and then mainly as surface run-off. The total surface infiltration (calculated by the HELP Model at about 5.3mm per year) over the next two years is estimated at less than 200,000 gallons, or 760,000 liters.

Water Balance Summary

The summary of water input requirements versus water consumption for two years of operation is given in Table 1. The values were calculated based on an average 40% moisture content within waste mass.

Table 1. Water Balance Estimates

Phase	Water Inputs/Production, Gallons (liters)	Water Consumption, Gallons (liters)	Net Volume Required, Gallons (liters)
Phase 1 (Prior to Operation or in the beginning)	3.88 E+07 (1.48 E+08)	None	3.88 E+07 (1.48 E+08)
Phase 2 (During Operation)			5.98 E+07 (2.27 E+08)
- Precipitation Infiltration (5.3mm/yr. over next 2 years	<200,000 (<760,000)		
- Hydrolysis/Biologically Mediated Oxidation Reactions	4.24 E+07 (1.61 E+08)	2.83 E+07 (1.08 E+08)	
- Vapor/Advection		7.41 E+07 (2.94 E+09)	

CONCLUSIONS

Water requirements in an aerobic bioreactor landfill environment can be estimated in two phases. These phases are (1) the initial amount of water needed to increase the waste moisture content to an operational and safe range and (2) the amount of water required for hydrolysis and biologically mediated oxidation to sustain microbial activities during operations. As discussed in the case study, the theoretical amount of water requirements can be calculated in an aerobic bioreactor landfill environment. Physically-based process models are essential for design of aerobic landfill systems. For a 35-acre landfill, the amount of water required initially for an aerobic bioreactor process is about 39 million gallons, which makes aerobic bioreactor processes not feasible if the source of water is remote or costly to bring to the site. Once the process is underway, the aerobic landfill is estimated to consume an additional 60 million gallons of water in order to sustain the aerobic process in a safe operational range of the moisture content.

The complex and dynamic interactions within bioconversion systems are a fundamental component of the knowledge base necessary for developing a sustainable landfill infrastructure. Yet, physical and biological processes occurring in most bioconversion systems are not well understood, primarily because of the myriad of possible substrates, climate conditions, geography, landfill geometries, waste characterization, and highly dynamic temperature-moisture conditions. Further, as many landfills in China were constructed with less daily cover (thus lower waste compaction) as compared to landfills where aerobic systems have been successfully operated, these differences will most likely have an effect on overall system performance.

This lack of understanding has resulted in much empiricism being the norm in current aerobic landfill remediation designs. Thus, collecting more site data as part of the initial site investigation work is necessary to improve water requirement estimates. Because there have been few aerobic landfill projects with comprehensive data on water consumption and production, that there are many complex reactions that can occur and affect water consumption or production, and the variability in the types of MSW and climates, there is no one equation for a water balance estimate or modeling. Therefore, there is a need for additional research in this area.

In addition, aerobic landfill operators have effectively managed several systems based on composting science and trial-and-error methods. As the science advances further, there has been an increase in study in the major aspects such as water application, temperature control, and fluid properties, which will ultimately aid in the design of cost effective aerobic bioreactor landfills.

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