BIODRYING BIOSOLIDS USING AN AGITATED BIN COMPOSTING SYSTEM

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Abstract

Evolving changes in biosolids management programs and industry demands prompted Siemens Water Technologies to conduct Mechanically Enhanced Biodrying (MEB) Pilot Studies as a new application for the existing IPS Composting System. The Studies determined the ability of the automated, agitated bin technology to achieve 65 percent solids concentration (35 percent moisture) in biosolids by using only the finished dried product as the amendment. Summer and winter studies focused on variables such as feedstock properties, turning frequency, bin retention time, and process aeration cycles.

The goal of 65 percent solids was achieved when the dewatered cake (Sludge) was at least 20 percent solids concentration with the volatile solids content of at least 60 percent and the combined in-feed mix (Test Mix) was 40 percent solids concentration or greater. Overall, the solids increased an average of approximately one percent per day and as much as two percent per day when minimum in-feed conditions were met.

The study addressed industry requests for a versatile end product that could be used for fuel or fertiliser and created by using less energy than traditional drying technologies. It also addressed a biosolids composting challenge when wood waste and other carbon rich amendments are in short supply.

Keywords

Biodrying, Biosolids, IPS Composting System, Sewage Sludge, Sludge Drying

Introduction

Biodrying is a biological process in which organic materials produce self-generated heat that evaporates water and thereby reduces the overall weight and volume of the feedstock. Mechanically Enhanced Biodrying (MEB) incorporates physical processes such as forced aeration and turning of the materials to expedite moisture evaporation during biodrying. In these studies, Siemens Water Technologies (Siemens) sought to apply the mechanical advantages of its IPS Composting System (IPS) to the biodrying principles and develop an engineered protocol to achieve the desired results.

Biodrying is on the spectrum between drying and composting. While many principles of composting and biodrying can be similar, there are significant differences with respect to wastewater Sludge or biosolids.[1] Biosolids composting requires a relatively high C:N ratio, high porosity, moisture maintenance, and a long process retention time to produce a marketable end product. Shredded wood waste or other cellulose bulking agents are used, moisture may be added during the composting stage, and a curing phase follows active composting. In biodrying, the goals usually are to stabilise, decrease both volume and moisture content, and retain the calorific value of the feedstock for end use as a fertiliser or a fuel. Therefore, woody amendments and moisture are not added during the biodrying phase and the retention time is shorter since no curing is required.

While biodrying has been used and promoted for on-farm manure management, only limited references document biodrying being applied as an engineered system to dry sewage sludge by Collick, et al. (2007), Choi, et al. (2001), VanBlarcom, et al. (2004) and Wright (2002). A rudimentary practice of biodrying occurs where sludge is removed from drying beds and lagoons, formed into piles or windrows, allowed to self-heat and eventually dry to various extents. However, this drying method tends not to be an engineered or mechanically enhanced process.

Photo 1: **Sludge Biodrying Windrows in China**

Because of exposure to the elements and extreme ambient temperatures, biodrying biosolids effectively outdoors can be a challenge. It also limits the amount of control over other variables that affect the achievement of target solids concentration, pathogen destruction and the time it takes to meet these target values. Variables such as pile depth, porosity, turning frequency, capacity and space, aeration rates, moisture content, and feedstock temperature can be more

[1] The term “Sludge” generally refers to untreated dewatered wastewater solids and “Recycle” to denote the processed or dried end product. “Test Mix” refers to the blended Sludge with Recycle

readily managed or engineered in an in-vessel automated, agitated bin system that has a high degree of process control.

MEB pilot studies were conducted at two different IPS biosolids composting facilities located in the northeastern part of the U.S.A. to demonstrate the viability of an in-vessel automated, agitated bin system to biodry Sludge using only the finished dried biosolids (Recycle) as amendment. The study at one plant was completed during the summer months and the study at the second plant was performed during winter months.

The studies were undertaken to demonstrate that MEB could be accomplished for several communities in Asia seeking cost effective solutions for sludge treatment and had limited bulking agents or amendment available. The rising cost of energy globally has also generated interest in examining biodrying technologies as a lower energy-consuming alternative to systems requiring fossil-fuels. Both pilot facilities were selected primarily because their climate and types of sludge are similar to those of the Asian communities.

Materials and Methods

Agitated Bin Technology

The Siemens IPS Composting System (IPS) is an in-vessel, automated, agitated bin, technology that utilises a series of concrete channels (bays) to process organic material in an active thermophilic composting phase for a period of 14 – 56 days depending on the type of feedstock. IPS biosolids plants are usually designed for a 21-day average retention time. Each bay is divided into independently controlled temperature and aeration zones. Forced aeration is used to maintain aerobic conditions and optimize temperatures within the compost material.

Each day, when a charge of blended feedstock is loaded into the front of the bay, an electro-mechanical agitator travels through the bay to simultaneously turn, shred, mix and move the compost material approximately 3.7 meters towards the discharge end. As one charge is discharged from the bay, space is created at the loading end to accept a new charge. (See Photo 2) The entire process is housed within an enclosed structure for protection from the weather well as to capture odours for treatment typically through a biofilter. The individual temperature and aeration zones along with the IPS agitator features enable a high degree of control and operational flexibility to adapt to varying feedstock characteristics and process situations.

Photo 2: IPS Agitator and Technology Equipment

Pilot Test Locations

The first study was performed in Bristol, Rhode Island, USA at the Anthony Dupont Composting Facility during June through August 2008. (Naylor, et al. 2009) To examine the effects of cold weather on the process, a second pilot test was performed at the IPS equipped Merrimack, New Hampshire USA Composting Facility during the winter months from late November 2009 through February 2010. Similar to their Asian counterparts, both facilities are located near the 42nd latitude and manage predominately undigested and waste activated sludge.

While the Bristol facility has 4 bays and the Merrimack facility has 15 bays, both are of similar design with bays measuring 67 meters long, 2 meters wide and 1.8 meters deep. At Merrimack, the winter pilot test was performed in Bay 1 adjacent to an exterior aisle, the most susceptible place for heat loss during cold weather conditions.

Both facilities were 15 years old at the time of the tests. The Bristol facility is equipped with a relatively new 30 HP (22.5 KW) agitator and Merrimack is equipped with originally supplied 25 HP (18.5 KW) agitators. Each bay has five aeration zones (A-E), each with a dedicated 3 HP (2.2 KW) aeration blower and wall mounted thermocouple. As in most IPS facilities, the thermocouple provides real time temperature feedback to the aeration blower control system. The beginning of each bay contains a concrete loading pad to receive a charge volume of 10.7 cubic meters of unprocessed material. Processed material falls into a common discharge pit at the end of the bays.

Biosolids

The Bristol IPS facility receives undigested sludge from the Bristol Wastewater Treatment Plant (BWWTP) that is dewatered via a belt filter press to a solids concentration averaging 25% and typically co-composts with shredded green waste.

The Merrimack Compost Facility processes sludge from the Merrimack Wastewater Treatment Plant (MWWTP). The Plant generates predominantly undigested sludge however also accepts anaerobically digested biosolids from an adjacent brewery and raw septage for processing. The staff at Merrimack estimates that typically 30% of their infeed flow is from the brewery. Primary and Secondary sludges from the MWWTP are dewatered via belt filter press. In the summer, the ratio of Primary to Secondary is about 60:40 and tends to flip during winter, when septage deliveries are lower. The solids content of the sludge varies between 10 – 25% in the winter with an average of about 17%. During the test, it was noted the brewery biosolids generation increased during the holiday season. Since secondary or digested sludges can be more difficult to dewater than Primary and generally have less energy, (Albertson, et al., 1991, p.6) its inclusion in the test provided a conservative measure of performance as well as some obstacles in the processing.

Objectives

The Bristol, Rhode Island summer pilot sought to:

1. Evaluate use of dried biosolids (Recycle) as a complete replacement for traditional woody or cellulose amendment.
2. Investigate biodrying potential and time required as well as pathogen destruction of a blended feedstock consisting of only dewatered cake and variously dried biosolids products.
3. Determine physical and biological limits of IPS System for sludge biodrying.

The Merrimack, New Hampshire winter pilot further sought to:

1. Confirm IPS system's capability to dry a 45% solids combined infeed mixture of dewatered sludge, recycled dried product and minimal amendment to 65% solids during the coldest season of the year.
2. Confirm the amount of recycled product generated is sufficient to meet process needs.
3. Determine average bay retention time to achieve the drying
4. Assess IPS ability to consistently achieve pathogen destruction temperatures through out test period.
5. Estimate the heating value of discharged product.

Test Procedures

Bristol, RI Pilot Study (Summer)

The Bristol study was performed in two phases. Phase I evaluated biodrying potential and time requirements while Phase II investigated pathogen destruction capabilities. To initiate Phase I, thermally dried undigested sludge pellets (Pellets) from a local municipal facility were used as substitute amendment until the trial could produce its own dried biosolids (Recycle). Phase II used Recycle discharged from the Phase I testing as amendment.

In both phases, Sludge was blended with dried biosolids (Pellets in Phase I and Recycle in Phase II) to create a Test Mix with a target solids content of 40%. The two process-related variables that could be controlled during the testing were aeration blower run time and agitation frequency to maintain energy levels and temperatures for adequate drying and pathogen destruction. With the IPS system, retention time depends on the number of agitations per week. Each agitation results in moving the mixture approximately 3.7 meters towards the discharge pit. For the 67 meter bay length, approximately 18 agitations are required for the Test Mix to pass through the bay.

Phase I

The study bay was first loaded with 5 charges of shredded green waste pre-test feedstock. This material served as an insulating buffer as well as a barrier to prevent tapering of the Test Mix at the discharge end of the bay.

The Test Mix for Phase I consisted of a blend of dewatered undigested primary plus waste activated Sludge at 22% solids and heat dried undigested sludge Pellets at 90% solids with a combined solids content of 40%.

Five Test Mix charges were loaded into the bay. Additional green waste charges followed the test charges to insulate and prevent material tapering towards the loading end. Of the five test charges, the middle three were deemed the target charges for monitoring.

During Phase I, the intention was to dry the material as quickly as possible and optimize the evaporative moisture loss potential. Aeration rates were maintained to hold temperatures in the range of 25˚C to 45˚C. Agitation frequency was originally set in Phase I to allow 40 days retention time. However, when the target solids content of 65% was reached on day 9, the frequency reverted to daily agitation to discharge the charges after 24 days to move onto Phase II. Multiple charges were sampled and tested nine times during Phase I.

Phase II

Test Mix for Phase II consisted of blending 22% solids Sludge with some Recycle from Phase I at 85% solids for combined solids of about 40% solids. Since Recycle particles were larger than the original Pellets, the porosity of the mix improved. Three charges of Test Mix were loaded with the middle charge deemed the target charge for monitoring. The Test charges were preceded and followed by charges of green waste as insulation barriers.

Aeration was managed in Phase II to achieve temperatures that meet regulatory compliance for Process to Further Reduce Pathogens (PFRP) and Vector Attraction Reduction (VAR)[2]. Temperature compliance was the major objective with achieving adequate drying the secondary objective. Agitation frequency was set at once every day (except Sunday) to take advantage of temperature increase associated with the agitation process. The material was retained in the bays for an average of 18 days with Charge 2 sampled and tested six times.

[2] Per United States Environmental Protection Agency Code of Federal Regulations Section 503 (USEPA 40 CFR 503) requires temperatures maintained for 72 hours (3 days) at or above 55˚C for pathogen kill equal to or greater than 55°C for 72 hours and equal for PFRP and 14 days at >40˚C for VAR. (USEPA ,2002)

Merrimack, NH Pilot Study (Winter)

The Merrimack study was also performed in two phases. The Pre-Pilot Test Phase created a dried biosolids product (Recycle) to blend with Merrimack's dewatered Sludge for the Pilot Study Phase to evaluate the MEB process under extreme temperature conditions. As with the Bristol test, a target solids content of 40% was desired for the Test Mix.

Pre-Pilot Test Phase

Since dried sludge product was not available to blend with Merrimack's Sludge, the Pre-Pilot Test phase was devised to produce the Recycle. Dried wood shavings at 85% solids were used to minimize both the amount of amendment required and decomposition time to create a Recycle with the least amount of wood present. The test bay was operated predominantly in 100% recycle mode, decreasing the amount of wood shavings after the first pass[3] and increasing the amount of Recycle and Sludge, as conditions warranted, to achieve the 40% solids for the Test Mix and 65% solids for the Recycle discharged at the end of the bay. Four "pre-test" passes (P1 – P4) were run from 24 September 2009 to the end of November. By the end of November, enough of the initial amendment had decayed whereby the Recycle was predominantly dried biosolids and operations began to simulate the MEB process marking the end of the Pre-Pilot Test phase and the beginning of the Pilot Test phase. Photo 4 shows the Sludge, Recycle and Sawdust ready to be mixed on the loading floor

Photo 3: Merrimack Test Mix prior to Mixing on Floor for Pass P4

[3] A 'pass' is defined as moving a designated charge and subsequent charges through a full cycle of 18 agitations in the bay and is therefore comprised of 18 charges. After 18 agitations, the designated charge is discharged and transferred as Recycle to be blended with Sludge to become the designated charge to start the next pass. Design scenarios were maintained for all 18 charges in any given pass, with new scenarios applied to each specific pass.

Pilot Test Phase

From late November 2009 through February 2010, four passes (1 – 4) were made through the bay to evaluate the MEB process under different scenarios. As in the first study, agitation frequency and aeration rates were adjusted to maintain energy levels and temperatures for adequate drying and pathogen destruction.

Pass 1 – The intent was to prepare a Test Mix with solids concentration as close to 45% solids as possible using Sludge at 20% and Recycle at 65% solids however as Table 1 below shows, the Sludge delivered averaged much less at 15.7% and subsequently produced Recycle with lower solids content. The volumetric ratio of Sludge to Recycle was about 1:2 with a weight ratio of slightly less than 1:1. Several charges required the addition of sawdust or screened compost to bulk up the Sludge. Since mixing best promotes drying, homogenizing and maturing the material, the intent was to agitate the bay 6 times per week to achieve 20 days detention. The goal for Zone A was to aerate sufficiently to keep the temperature above the 55°C point to achieve PFRP and, for Zones B – D, to aerate as needed to optimize drying.

Pass 2 – The intent was to prepare a Test Mix similar to Pass 1 but agitate less frequently at 5 times per week to see if any significant gain in solids content resulted from the increased retention time and decreased agitations. Due to the low solids content of the delivered Sludge (average of 15%) throughout Pass 1, the amount of the Recycle was increased to a volumetric ratio of Sludge to Recycle to about 1:2.7 resulting in a Test Mix comprised of average 17.7% solids Sludge and 50% solids Recycle for an average of 37 -38% solids. Pass 2 did not require any addition of sawdust or screened compost.

The focus of aeration for Zone A was to maximize drying efficiency as well as keep the zone above 55°C consistent with PFRP pathogen destruction guidelines. The goal for Zones B - D was to aerate as needed to optimize drying.

Pass 3 – The intent was to load and agitate the bay daily if at all possible for 20 days. Because the incoming Sludge was low at about 16% solids and the Recycle solids were not increasing, the same Test Mix Sludge to Recycle ratio of 1:2.7 was maintained. It was not necessary to add sawdust or screened compost during Pass 3. The focus of aeration for all zones was to aerate as needed to optimize drying.

Pass 4 – The intent was to mimic longer bays with increased retention time while trying to agitate daily. This was achieved by reloading material that was discharged back into the front of the bay without adding any fresh Sludge or additional Recycle. The average retention time for Pass 4 was expected at 25 days to give the Test Mix a total of 45 days to make two passes in the bay. The focus of aeration was to aerate and agitate to optimize drying.

A summary of the design parameters for each pass as well as the volumes and solids contents of the various components for the Test Mix of each Pass are shown below in Table 1.

Table 1: Summary of Input MEB Test Passes

Merrimack, New Hampshire Mechanically Enhanced Biodrying Pilot Test
TEST PASSES - NOVEMBER 2009 to FEBRUARY 2010

PASS	GOAL	VOLUME PER CHARGE SLUDGE (m3)	VOLUME PER CHARGE AMENDMENT (m3)	VOLUME PER CHARGE RECYCLE (m3)	AVERAGE SOLIDS CONTENT SLUDGE (ds)	AVERAGE SOLIDS CONTENT RECYCLE (ds)	AVERAGE SOLIDS CONTENT TEST MIX (ds)	NOTES
P4	Sludge only Recycle	≈ 2.5	≈ 1.3	≈ 9.1	19.7%	≈54%	≈ 43%	Highest sludge ratio in pretest
1	>40% input to 65% in 20 days no sawdust	≈ 4.2	(≈0.8 added to 3 charges) to bulk up wet sludge	≈ 9.1	15.7%	≈61%	≈ 41%	Trying to hit design input values
2	>40% input in 25 days no sawdust	≈ 3.6	0	≈ 10	17.7%	≈51%	≈ 37%	Increase Recycle to offset wet sludge Need to agitate daily
3	>40% input agitate every day in 20 days	≈ 3.4	0	≈ 10.7	15.9%	≈48%	≈ 37%	Too much H20 halt test. Try running longer with/no new sludge
4	Recycle only agitate every day in 20 days	0	0	≈ 10.7	NA	≈48%	≈45%	Effectively extending bay length Water Increase???

Sampling, Temperature Readings and Laboratory Testing

The Test Mix and conditions were monitored for solids content and temperature during both Pilot Studies with solids analyses performed by onsite laboratories at each plant. Data logging probes were inserted into the center of each aeration zone to record temperatures on a daily basis.

At Bristol during Phase I, multiple charges were sampled and tested nine times during the 25 day drying period. During Phase II, Charge 2 was sampled and tested six times during the 18 day drying period. Single grab samples were taken from the center of each charge.

At Merrimack during both phases, single grab samples of the Test Mix were taken 2 to 3 times per week for solids analysis after agitation from 10 locations corresponding to two in each of the 5 aeration zones in the bay. Weekly single grab samples of the Sludge, Test Mix and Recycle that were tested for solids, nutrients, minerals, and metals were shipped to off-site laboratories for further testing following Standard Methods and traditional accepted analytical protocols. Samples were also tested for stickiness, 5 day biochemical oxygen demand (BOD5) and specific oxygen consumption rate (SOCR) per Standard Methods, 2710B.

Ambient temperatures also were recorded daily and were analysed for possible impact on or correlation to the biodrying rate and temperature of the Test Mix.

Pilot Study Variables

Uncontrollable variables:

- Biosolids Solids
- Physical/Chemical Properties of the Sludge In Bay Volume Reduction

- Infeed/Discharge Densities
- Ambient Air Temperature and Humidity

IPS MEB Controllable Variables

- Bay "Charge" Size
- Test Mix Composition
- Aeration Zone Blower Runtime
  - *Time & Temperature Mode*
  - *Aeration Matching Agitation Mode*
- Aeration Zone Temperature
- Agitation Frequency

Results and Discussion

Validity of Drying Potential

The Bristol study demonstrated product generated from the mechanically enhanced biodrying process using only Recycle as amendment, can achieve up to 70% dry solids as well as meet PRFP and VAR parameters. It also demonstrated the IPS equipment was mechanically capable of processing a sludge/biosolids only mix. The Merrimack study determined when ambient temperatures reach as low as -10° C, the product can achieve 60% dry solids or greater provided the Sludge is 20% dry solids or greater with a volatile solids content greater than 60%.

Results from both studies indicated that biodrying as well as PFRP and VAR can be achieved in warm weather, whereas drying to 65% solids may be compromised when inadequately dewatered sludge (15-17% solids content) is encountered due to seasonal fluctuations. Through close monitoring of the aeration and agitation strategy, however, the process can still succeed in meeting PFRP. Although the agitator machine was powered by relatively low horsepower motors, the equipment was mechanically able to process the sticky input mixture and maintain system capacity even as conditions declined..

Based on Siemens' past experience with compost facilities, operations and similar materials, it was anticipated that handling and composting of the Sludge using Recycle would be both physically and chemically demanding on the process as well as the equipment. It was also anticipated that serious problems could occur from biodrying dewatered undigested primary sludge combined with waste activated or digested sludge; problems related to odor, stickiness, low porosity and mechanical challenges that could result in inadequate drying and pathogen kill as well as poor product quality. It is encouraging that none of these issues were encountered in either of the two studies.

Moisture Content Profiles and Pathogen Destruction Discussion

Bristol

Phase I

The strategy to run the aeration blowers to dry the material out as quickly as possible was successful. Temperatures reached 5°C above ambient temperatures quickly by day 2. The solids content increased from 43% to achieve the target 65% solids by day 9 and reached 88% by Day 24. Odours were minimal and not considered to be objectionable. Fecal coliform counts in the Recycle ranged from 19 to 1,100 Most Probable Number (MPN) per gram dry solids and averaged 500 MPN per gram dry solids. Photo 4 shows the product consisting of dried sludge with some remaining pellets.

Photo 4: Bristol Study Phase I Biodried Product

Phase II

During the18 day retention time, solids content rose from about 41% to about 68%. Temperatures were maintained in the 40˚C to at least 55˚C range for 13 days, with temperatures exceeding 55˚C for 8 consecutive days - more than sufficient time/temperature days to meet PFRP. Consistent with this, the fecal coliform counts in all six of the Phase II Recycle samples were well below the 1,000 MPN per gram dry solids USEPA requirement. Although the requirement for VAR of 14 days at >40˚C was not fully achieved during this trial, the 14 day average temperature exceeded 55˚C.

Merrimack

Pre-Pilot Test Phase

The four 'pre-test' passes met the goal of producing Recycle that was predominantly dried biosolids to use as amendment for the Pilot Test and was successful in achieving a 65% solids Recycle from a 45% solids Test Mix by the second half of Pass P4. This success indicated the compost process and mechanical robustness of the agitator would be able to achieve the MEB goals.

Photo 5: Moisture Released through Agitation w/Aeration: Bay 1, Merrimack Study

It is important to note that Pass P4 was the only pass during the study to have an average 20% solids Sludge available for the Test Mix which consisted of blended Sludge and Recycle at a volume ratio of 1 part Sludge to 3 – 3.5 parts Recycle to 0.5 parts sawdust (if needed to achieve the 45% solids Test Mix). The charges in Pass P4 had the highest ratio of Sludge to Recycle during the Pre-Pilot Test phase.

Pilot Test Phase

The intent was to run each of the four passes under a different scenario to evaluate various aspects of the MEB process. Unfortunately, the Sludge delivered during Pass 1 averaged only about 15.7% solids and had a pervasive negative and cascading impact on the ability to achieve the desired Test Mix and Recycle solids contents consistently for the remainder of the test period as demonstrated in Table 2 - Summary of MEB Output Test Passes. Table 2 shows the 75 day test period for Passes P4 – 3 broken down into half pass (10 day) segments, except for Pass 3 which encompasses 15 days. The Infeed and Output data are averaged over the 10 day segments and are shown to decrease over time due to the deficiencies created by the fluctuating and declining Sludge solids content.

Table 2: Summary of MEB Output Test Passes

Merrimack, New Hampshire Mechanically Enhanced Biodrying Pilot Test OUTPUT DATA TEST PASSES 1 T0 3 TEN DAY AVERAGES & TEST PASS 4									
	AVG SOLIDS CONCENTRATION		RECYCLE	AVG	INPUT	AVG	AMBIENT	TEST	NOTES
PASS	SLUDGE (ds)	RECYCLE (ds)	DENSITY (kg/m3)	TEST MIX (ds)	DENSITY (kg/m3)	RECYCLE (% ds)	TEMP (°C)	DAYS	OUTPUT data is from 20 days later i.e
P4-1 3-Nov 12-Nov	≈20%	≈52%	NA	≈42%	NA	≈55%	HI ≈12 LO ≈0	P1 -P10	Highest Recycle solids content during Pretest
P4-2 13-Nov 22-Nov	≈19%	≈55%	NA	≈44%	NA	≈65%	HI ≈10 LO ≈ -3	P11 - P20	Dry Sludge and Recycle reach the target
1 23-Nov 2-Dec	≈17%	≈55%	500	≈40%	600	≈61%	HI ≈10 LO ≈ -3	1 - 10	BEGINNING OF TEST PERIOD
1 3-Dec 12-Dec	≈16%	≈65%	520	≈42%	710	≈50%	HI ≈3 LO ≈ -10	11 - 20	Brewery Sludge spikes ahead of Christmas Holiday
1 13-Dec 22-Dec	≈15%	≈61%	460	≈38%	675	≈49%	HI ≈ -5 LO ≈ -13	21 - 30	Recycle solids dropping with Sludge solids
2 23-Dec 1-Jan	≈17%	≈50%	520	≈37%	675	≈48%	HI ≈ 0 LO ≈ -7	31 - 40	Sludge solids rising but recycle is so wet now
2 2-Jan 13-Jan	≈17%	≈49%	640	≈38%	675	≈48%	HI ≈ -3 LO ≈ -10	41 - 50	Sludge volume dropping and thus energy of mix
3 14-Jan 26-Jan	≈16%	≈48%	640	≈37%	675	≈48%	HI ≈ 5 LO ≈ -10	51 - 65	Not getting anywhere stop test after 13 days
4 26-Jan 26-Feb	NA	≈44%	620	EQUALS RECYCLE	EQUALS RECYCLE	≈47%	HI ≈ 3 LO ≈ -5	20 Day Avg	Recycle picking up moisture from wet discharge floor

Pass 1 – Achieving a 45% solids Test Mix and 65% solids Recycle was difficult as the Sludge solids content declined significantly to as low as 10% solids. By the middle of Pass 1, excess Recycle was generated meaning more Recycle was produced than was needed to blend at the 2:1 volume ratio with the Sludge. As Pass 1 progressed and the Sludge solids content declined, Siemens opted to reduce the Sludge volume and increase the Recycle volume to keep the Test Mix above 40% solids which in turn negatively impacted the available energy in the mix. For the few charges when Sludge solids were between 10 - 13%, small amounts of sawdust or screened finished compost from another bay were added for bulk as too wet a mix would have not been useful to the test process.

Temperatures ranged between 58° to 70°C throughout Pass 1, so the goal to keep Zone A above the 55°C point was reached. The solids content data show the majority of drying occurs in Zones B – D.

Pass 2 – The effect of increased retention time on the solids content was difficult to determine due to the varying moisture levels of both the Sludge and Recycle during Pass 2. Even though the solids content of the Recycle discharged from Pass 2 did not reach the targeted 65% solids and ranged from 45% to 52 %, the Pass did provide a good example of how the solids and energy content of the Sludge and Recycle affects drying ability. Comparing two charges from Pass 2 to a charge from Pass 1 yielded the following results in Table 3 and shown on Table 1:

Table 3: Solids/Energy Content of Biosolids and Recycle vs. Drying Ability

Charge Date	Pass	Sludge (% ds)	Recycle (% ds)	Infeed (% ds)	Discharge (% ds)	Solids Increase (% pts)	Retention Time (days)
30-Nov	**1**	**17.2 %ds**	**60**	**38**	**61**	**23**	21
27-Dec	**2**	16.8 %ds	50	44	52	8	21
5-Jan	**2**	15.7 %ds	48	39	45	6	21

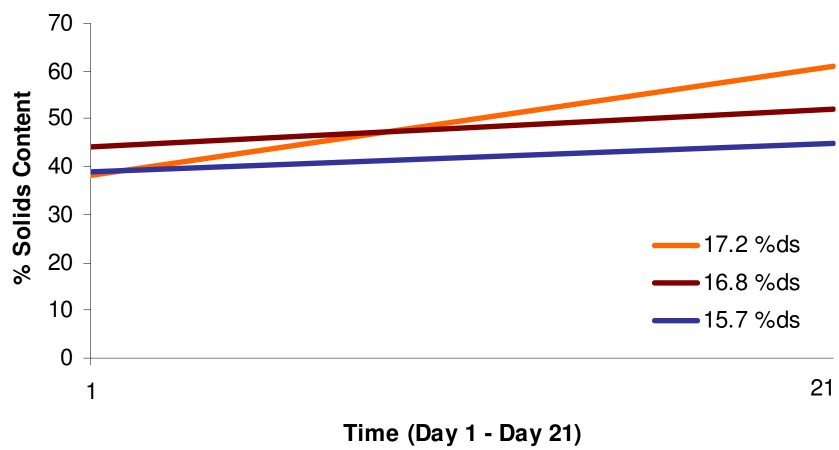

Figure 1: Solids Content Test Mix vs. Time – Charge comparison

Because the ratio of Sludge to Recycle was greater in Pass 1 than in Pass 2, more energy was available in the mix. The wetter charges in Pass 2 were unable to maintain the same rate of drying as Pass 1's dryer charges suggesting energy levels were too low and impacted the rate of drying with increases as low as 6 percentage points. Figure 2 below shows the flattening of the dryness curve through Zones D and E as the energy is depleted. The secondary goal of pathogen kill was achieved in this Pass as temperatures in Zone A stayed above 55°C for the minimum 3 days.

Pass 3 – Since the Sludge and Recycle solids contents continued to decline as Pass 3 progressed, Pass 3 was aborted after 12 days as further testing wouldn't reveal any new information. The data did show that Test Mix and Recycle values were consistent with those obtained during Pass 2 despite the lower solids contents so increased agitation frequency or the aeration scheme likely had a positive impact.

Pass 4 – Because an overhead door froze shut, water condensed and was unable to drain away leaving a puddle in the discharge pit where the Recycle from Pass 3 was deposited. Since the Recycle solids were several points lower when loaded into the bay for Pass 4, it was evident the Recycle absorbed some of the water.

Pass 4 was aerated to maximize dryness; however, the documented lower temperatures suggest the Test Mix was weak in energy content at this point. Even though the test was skewed by the moisture issues, it is apparent the remaining energy level would result in only a nominal gain in dryness by increasing the retention time and the expense to increase the bay length is not warranted.

As stated through this paper and shown in the data, the energy potential of the Test Mix is one of the most important variables affecting the solids content of the biodried product.

Ambient Temperatures

During the Merrimack Pilot Study, December temperatures were below the high/low average ambient temperatures for Merrimack at 0°C/-10°C , January was fairly consistent with the average 0°C/-10°C and February was warmer than normal at +3°C/-5°C . During the coldest period in December, the Test Mix temperatures consistently reached the high 60s and 70s in Zone A. Being able to achieve the desired biodrying rate and PFRP for Pass 1 during relatively cold ambient temperatures demonstrated that the MEB can be successful in cold climates.

Biological Performance

Heat: The Bristol Study data shows the biochemical process produced more than adequate heat to achieve both drying and pathogen kill goals through management of the aeration/agitation strategy. Temperatures of the target charges were continually monitored with data logging probes and demonstrated that regular agitation contributed significantly to maintain the heat output.

The modified aeration strategy combined with daily agitation was successful in maximizing temperatures in the Test Mix to achieve PFRP as well as maintaining heat output as shown in Figure 2 below. (See also Figure 6 and associated discussion.) Lower aeration rates allowed the Test Mix to conserve moisture and retain heat while daily agitation re-energized the process by re-mixing to make food sources available for the microbes. Even though VAR temperatures were only nearly achieved (13 days at greater than 40°C vs. the required 14 days), extending this time over 14 days can be readily accomplished with minor adjustments to moisture, aeration strategy and compost retention time.

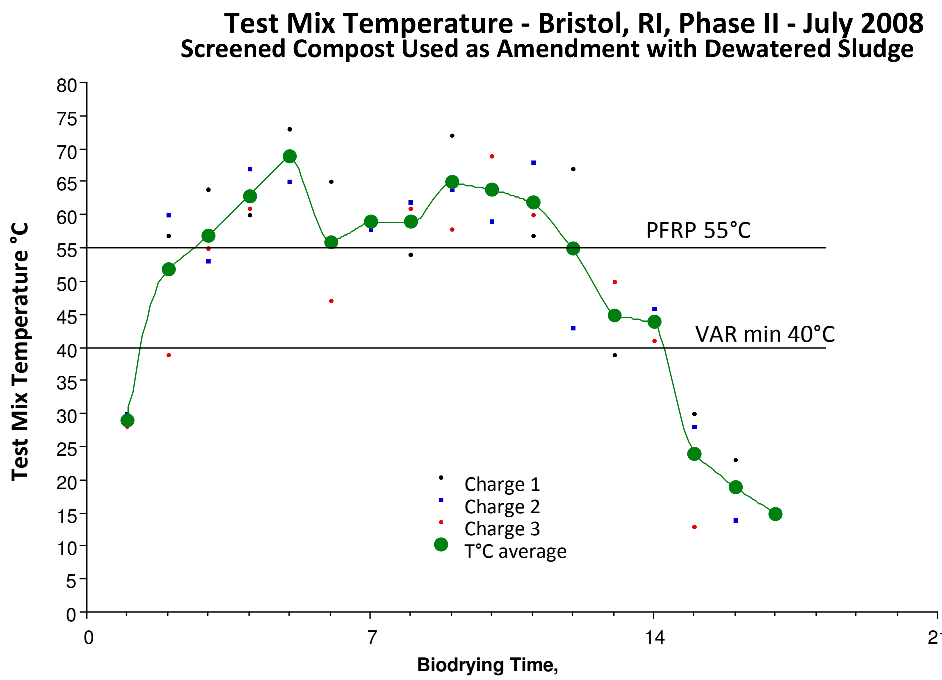

Figure 2: **Charge Temperature Profile for Bristol Phase** (Naylor, et al., 2009)

During the Merrimack Study the temperatures increased very quickly but since the strategy was to aerate continually, maintaining temperature was not a priority. When drying rates dropped, aeration rates were elevated to maximize the drying, which in turn caused the temperatures to drop as shown in Figure 3 below.

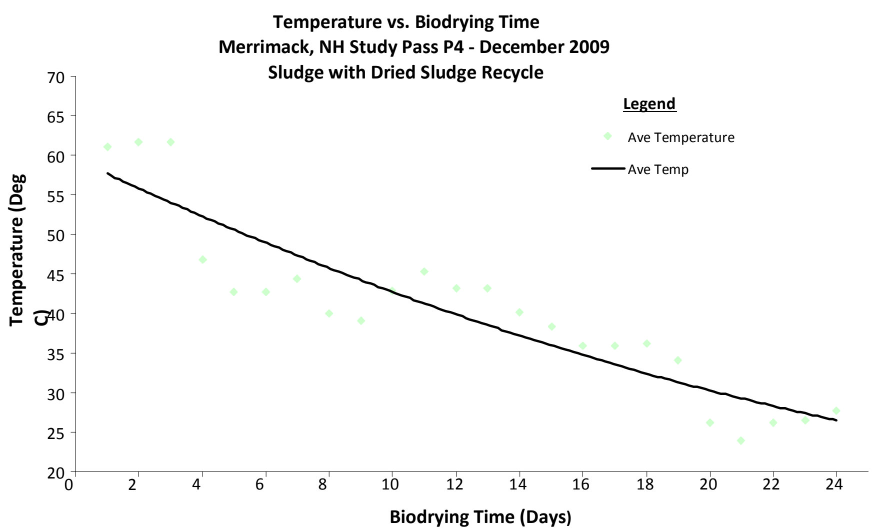

Figure 3: **Temperature Profile for Merrimack Pass P4**

It was learned that heat produced by the biochemical process was most affected by the characteristics of the Sludge. While the extreme ambient temperatures were expected to affect the process performance, it was actually variations in Sludge properties due to the seasonal increased ratio of secondary to primary sludge in the Test Mix that created obstacles during the Study.

Solids Content/Volatile Solids: An accelerated rate of drying of the Test Mix was obtained during Bristol Study Phase I. Illustrated below in Figure 4 is the effect of rapid composting (conversion of volatile solids into carbon dioxide, water and heat) on moisture loss and drying during days 1-7 of Phase I. As volatile solids were lost, biological activity diminished and reduced the heat output and rate of moisture loss. The Test Mix achieved about 80% solids within 14 days reaching maximum dryness (about 85% solids) 7 days later.

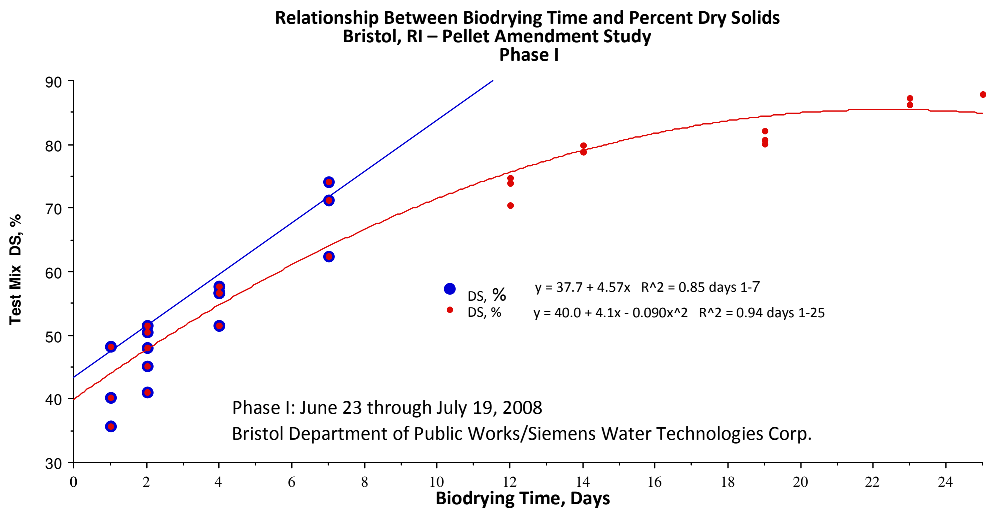

Figure 4: **Bristol Phase I Change in Solids Concentration over Biodrying Time** (Naylor, et al., 2009)

Volume Reduction: The loss of moisture and volatile solids during the biodrying process results in a loss of volume of the Test Mix as it travels down the bay. Photos 6 and 7 below show the volume reduction in the bays as the pile height decreases towards the discharge end at both Bristol and Merrimack. The amount of reduction can vary based upon the properties of the Sludge and Recycle. There appeared to be about a 20% reduction at Bristol and Merrimack when conditions were favorable. Sufficient dried product will be generated to support the process as amendment with excess available for fuel or fertilizer.

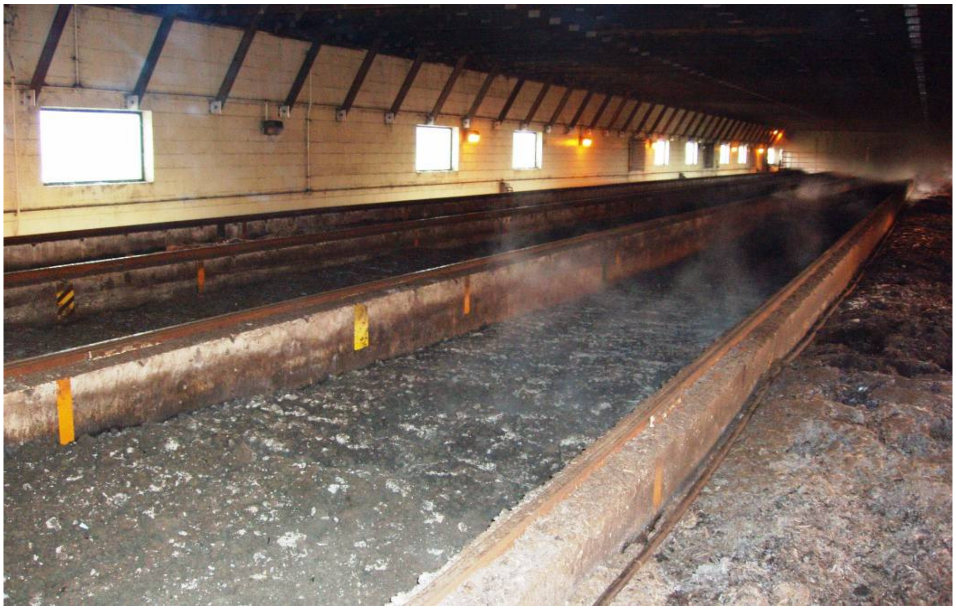

Photo 6: Bristol Study MEB Product Height Profile Down the Bay

Photo 7: Merrimack Study MEB Product Height Profile Down the Bay

The positive affect of the modified aeration protocol on material drying during Phase II can be seen below on Figure 5. Even though aeration rates were lower, the Recycle still achieved 68% solids during the 3 week period. Also shown is the comparison to the rate of drying achieved during the Merrimack Study.

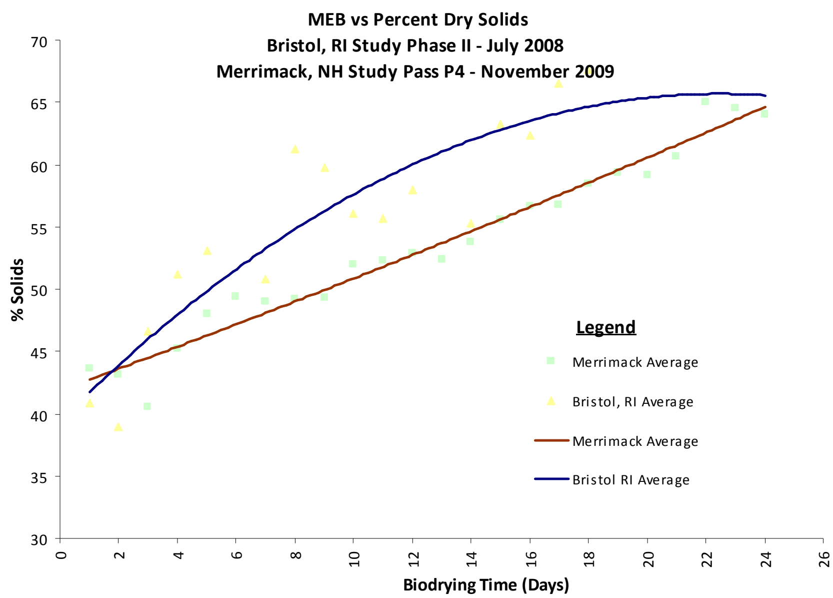

Figure 5: **Change in Average Solids Concentration over Biodrying Time** (Naylor, et al., 2009)

Mechanical Performance

Aeration: The initial strategy for both Studies was to run the aeration blowers to dry out the material as quickly as possible. As shown before, Bristol Phase I, temperatures quickly achieved the target 65% solids by day 9. During Phase II, the target charges achieved and maintained temperatures in excess of 55°C with PFRP reached by day 5 with solids content increase from 41% to 53%. Decreasing the blower time reduced the rate of drying to keep the compost active. By day 15, the solids content exceeded 60% and temperatures declined.

During Merrimack's Pilot Test Phase, different aeration schemes were applied throughout the passes to address deficiencies with the Test Mix. Because the Sludge solids concentration and volatile solids content fluctuated, the infeed conditions never reached a steady state and a set strategy could not be developed. This demonstrated that MEB aeration rates have to be tailored for specific Sludge properties and energy content.

Agitation: During Bristol Phase II, daily agitations succeeded in increasing temperatures and achieving PFRP and effectively achieving VAR while also achieving the target dryness of 65% in 18 days. The temperature increase associated with each agitation for Charge 4 from Phase I is shown in Figure 6 which shows compost temperature as a function of compost time. Note the improved heat output (temperature spikes) with each agitation.

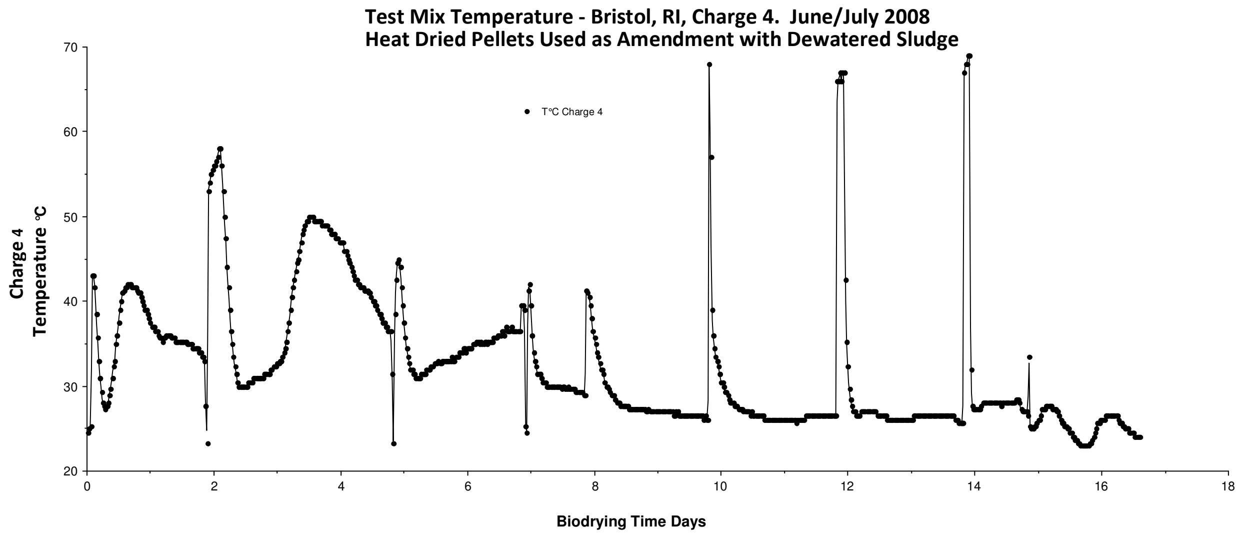

Figure 6: Phase I, Charge 4 Temperature Profile (Naylor, et al., 2009)

In both studies, daily agitation provided a number of benefits including: physical reduction, increased porosity and homogenization of the Test Mix to enable microbes to access nutrient, water and carbon sources for energy.

As discussed above, it was expected that the agitator would struggle mechanically moving through the Test Mix, especially at the loading end with the highest pile height. The agitator amperage draw was measured throughout the length of bay multiple times during the Bristol Study and showed only a 10% (5 amps) average increase (within acceptable limits) as the 22.5 KW agitator moved through the target charges at the loading end and no significant increase after day 3 in the bay.

While amperage measurements were not repeated in Merrimack, the 15 year old 18.5 KW IPS agitator showed no signs of stress when mixing and moving the wetter, denser Test Mix as well. Table 4 shows the 22.5 KW agitator has a lower power to area ratio than the latest models 37.5 KW and 74.5 KW IPS agitators which should be more than capable to process this type of material in future applications.

Table 4: Agitator Power to Area Ratio Summary

Agitator Motor Power (HP)	(KW)	Area Cross Secion (m2)	Power:Area Ratio (KW/m2)
25	18.5	3.7	5.0
30	22.5	3.7	6.1
50	37.5	4.6	8.1
100	74.5	7.0	10.6

Power Consumption: The major energy consuming equipment utilized for both studies included the aeration blowers, the agitator and the loader. Ancillary equipment such as HVAC fans, lights, other loaders for material movement, etc. were not considered, but are potential sources of significant energy demand.

Mixing the Sludge and Recycle on the floor was accomplished with a diesel powered John Deere 240 (40 KW) skid steer loader. Aeration was provided to the bays by 2.2 KW aeration blowers, one for each of the five zones with run times varied in each zone for both phases of both Studies. For Bristol, during Phase I, the bay was agitated five times over 9 days to achieve the target dryness with 16 agitations accomplished for Phase II. In Merrimack, the bay was agitated 5 or 6 times per week. From the above scenarios, consumption was calculated on a per unit of Test Mix basis.

The varied aeration and agitation strategies for Phases I and II of Bristol resulted in energy consumption being greater to achieve PFRP and VAR in Phase II. At Merrimack where the design conditions were not achieved on a regular basis, the blower average run time was estimated to be about 3 hours per day based on the strategy used during Pass P4 as well as knowledge from the Bristol Study. Both Studies assumed the agitator was at full power demand for the entire length of the bay when realistically, that was not the case. Table 5 is a summary of the energy consumption as determined by both Studies:

Table 5: **Energy Consumption per Unit of Test Mix** (Naylor, et al., 2009)

	Power Consumption per Cubic Meter of Test Mix	**Power Consumption per Tonne of Test Mix**
Bristol – Fuel	0.4 liters	0.8 liters
Bristol - Electricity Phase I	1.8 KWH	3.4 KWH
Bristol - Electricity Phase II	2.9 KWH	5.9 KWH
Merrimack - Electricity	8 KWH	15 KWH

Assumes average density of test mix at 0.53 tonnes/m^3

Estimated Heat Value

To estimate the Higher Heat Value (HHV) of the finished dried biosolids (Recycle) from the MEB process, an equation from the fuel wood industry was used for calculating heat value of wet wood, then modified to include the VS content of the material. (Panshin and deZeeuw, 1980, p. 218)

Calculations for the Merrimack MEB output from Pass 4 at 48% resulted in an adjusted (for moisture) heat value of about 2,100 kcal/kg. If the Pilot Test had achieved the target 65% solids content, the Expected Merrimack MEB output Heat Value would rise to about 2,400 kcal/kg or 10,150 kJ/kg. Varying composition of sludge (VS, fats, proteins, carbohydrates, etc.) can vary the MEB outputs. The estimated HHV of 2,400 kcal/kg for a 65% MEB product is slightly less than the value for 50% moisture wood at 2,910 kcal/kg or 12,300 kJ/kg (5,270 Btu/lb) listed by the reference. Estimated values are listed for the Bristol and Merrimack MEB products in Table 6 below.

Further comparison to a derivative of Dulong's formula that Haug (1993, p.111) has found useful in estimating gross heating values from the feed composition yielded a lower value of 8,500 kJ/kg for the HHV. It is recommended to use the more conservative value until testing can be performed.

Table 6: Estimated Heat Value of Biodried Biosolids (Haug, 1993, p.110)

Wet Wood - 50% Solids[d]

$$\frac{Btu}{lb} = H_c \times \frac{100 - \left(\frac{MC}{7}\right)}{100 + MC} = \frac{8{,}500\,Btu}{lb} \times \frac{100 - \left(\frac{50}{7}\right)}{100 + 50} = 5{,}270\,\frac{Btu}{lb}$$

Given the Heat value of dried wood is 8,500 BTU/lb (19,800 kJ/kg):
The Heat Value of 50% ds wood calculates to be 5,270 BTU/lb (12,300 kJ/kg)

Using the above equation for compost, for this application only the Volatile Solids (VS) have energy

	Volatile Solids % of Dry Solids	Heat Value Dry VS (kJ/kg)	Heat Value Dry Bulk Solids (kJ/kg)	Dry Solids Content (%)	Moisture Content (%)	Adjusted Heat Value for Moisture (kJ/kg)	Adjusted Heat Value for Moisture (kcal/kg)	Notes
Wet Wood	-	19,800	-	50	50	12,300	2,910	
Typical Compost	87	23,260	20,240	55	45	13,060	3,090	
Merrimack MEB Output	62	23,260	14,420	48	52	8,780	2,080	(Lowest Average Recorded)
Expected MEB Output	62	23,260	14,420	65	35	10,150	2,400	(20% Sludge & 45% Test Mix)
Bristol MEB Output	79	23,260	18,380	68	32	13,290	3,140	(Pass II/Charge II)
Estimated MEB AVG	**60**	**23,260**	**13,960**	**65**	**35**	**9,820**	**2,320**	(Based on China samples)
		kcal/kg	**kcal/kg**					
		5,500	**3,301**					

Sources: [d] Equation from *Textbook of Wood Technology* - Panshin, A.J. and C. deZeeuw. 1980.
[e] 23,260 kJ/kg (10,000 BTU/lb) from *The Practical Handbook of Compost Engineering* - Haug, Roger, 1993

Conclusions

1. Mechanically Enhanced Biodrying (MEB) relies on both biological and mechanical processes being successful. Robust biological energy drives the evaporation of water to dry the material while turning the material routinely is essential to mix and provide porosity to enhance the moisture release. MEB's success relies on the energy produced by biodegradation of volatile solids (VS) to warm the infeed mixture, evaporate moisture, and dry it without supplemental energy source or amendment. These MEB studies determined that the VS content for Sludge must be a minimum of 60%. VS content lower than that threshold appeared to compromise the effectiveness of biodrying.

2. The results of the MEB Pilot Studies at both Bristol and Merrimack demonstrate that dried biosolids can be used as a replacement for traditional woody amendment to biodry sludge in varying climates in an in-vessel agitated bin system.

3. The pilot studies provided sufficient results to conclude that the IPS MEB process produces a >60% solids finished product regardless of cold weather conditions within the following minimum constraints:
   a. 20% Sludge solids concentration

   b. 60% Sludge volatile solids content
   c. 45% Infeed Mixture solids concentration

4. Conversely, the effectiveness of the MEB process appeared to wane when the solids concentration of the dewatered Sludge was significantly lower than the desired MEB test criteria of 20% solids and the VS was below 60%. While the mechanical performance of the agitator equipment was successful during the MEB studies, the challenge during the Merrimack Study occurred when the dewatered Sludge samples tested at 15 % - 17% solids concentration and resulted in a biodried product emerging at 47% to 50% solids. This phenomenon was attributed to a decrease in the ratio of undigested to anaerobically digested sludge that resulted in a sludge that dewatered poorly with lower volatile solids content and not enough energy to maintain adequate temperatures for moisture removal. This outcome further substantiated the desired parameters for the solids concentration and volatile solids.

5. Varying characteristics of the Sludge such as solids concentration and VS content will determine the length of time required in the MEB process to biodry and meet pathogen destruction requirements. Those with higher concentrations have higher energy potential and will achieve target dryness and temperatures more readily. If the input parameters are met, the average bay retention time in the IPS MEB will be 20 days to achieve a 20 point gain in dryness..

6. The IPS equipment performed well even though the mix created by Sludge and dried biosolids was denser than typical IPS applications. Even the wet and sticky mixtures experienced in Merrimack did not impact the performance of the older model agitator and blowers.

7. Based on the observation of a bay volume reduction at about 20%, sufficient volume of product at >60% solids concentration to meet amendment and end use needs will be generated via MEB, provided the input parameters are met.

8. Both studies indicate there should be sufficient time and energy in the MEB process to achieve pathogen destruction requirements. Ambient temperatures as low as -10°C did not make a significant impact on the ability of the Test Mix to generate heat in the bays and, therefore, did not impact the ability to biodry and meet PFRP.

9. As the Merrimack study did not achieve the 65% solids end product, the heat value of the output was not able to be tested. Calculations herein estimate the higher heat value (HHV) of the final product to be 8,500 kJ/kg, which is slightly less than the heat value 50% wet wood.

Acknowledgements

The authors gratefully acknowledge the administrators and staff at the Anthony Dupont Composting Facility in Bristol, Rhode Island USA and at the Merrimack, New Hampshire USA Composting Facility.

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