Composting Bioreactors

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March 2014

A thesis submitted to McGill University in partial

fulfillment of the requirements of the degree of Masters in Science

ABSTRACT

Composting is an increasingly popular method of municipal, retail, and residential waste management. Uniform composting is necessary to obtain a consistent product and to ensure the destruction of pathogens. It is therefore essential to maintain a homogeneous temperature throughout the compost. To better accomplish this, a compost vessel with a heat redistribution system (HRS) was designed, constructed and tested. This system was composed of a heat exchanger, plastic tubing, and a copper coil filled with water. The system moves heat from the warmer center of the compost bed to the cooler areas at the outside and bottom of the bed without external inputs of energy. Once composting begins, the temperature of the water inside the heat exchanger rises, and buoyancy effects cause the water to flow through the copper tubing, distributing the core heat throughout the compost. Heat is also redistributed by conduction along the copper tubing. The heat redistribution system can be used in applications requiring assurance of uniform composting conditions and a high-quality product.

Previously obtained test data suggested that the HRS system had accomplished its goal, but it was noted that high amounts of heat loss occurred through the 10.16 cm hole at the top of the vessel. The compost vessel was then redesigned to include an air heat exchanger (AES) to address this issue. This system's objective was to reduce heat loss from the top aeration hole. A total of twelve compost-vessel experiments were run: four with the heat redistribution system, four with the air exchanger system and four controls. The vessels were fitted with thermocouples at different levels, 33, 54 and 84 cm from the bottom of the vessels, to monitor temperatures. The HRS vessels demonstrated higher temperatures within the first 10 days of the experiment $p<0.001$.

RÉSUMÉ

Le compostage est une méthode de plus en plus populaire pour la gestion municipale et résidentielle des déchets. Le compostage uniforme est nécessaire pour obtenir un produit homogène de haute qualité et assurer la destruction des agents pathogènes. Il est donc essentiel de maintenir une température uniforme dans tout le compost. Pour mieux y parvenir, un récipient de compost équipé d'un système de redistribution de la chaleur (HRS) a été conçu, construit et vérifié. Ce système est composé d'un échangeur de chaleur, un tube en plastique, et une bobine de cuivre rempli d'eau. La digestion bactérienne des matières organiques cause une augmentation de la température de l'eau à l'intérieur du HRS et provoque un effet de flottabilité qui enchaîne un déplacement d'eau à l'intérieur du tube de cuivre, distribuant la chaleur du centre le plus chaud du compost vers les zones plus froides et ce, sans apport d'énergie externe. La chaleur est également redistribuée par conduction le long du tube de cuivre.

Les résultats obtenus suggèrent que le HRS atteint son objectif, mais des pertes de chaleur ont été découvertes à la sortie d'air de 4". Un échangeur de chaleur à air (AES) a été ajouté pour réduire la perte de chaleur. Un total de douze expériences ont été effectuées : quatre avec le HRS, quatre avec l'AES et quatre contrôles. Les vaisseaux été équipés de thermocouples placés à 33, 54 et 84 cm du sol. Les vaisseaux équipés du HRS ont démontré des températures plus élevées au cours des 10 premiers jours de l'expérience ($p < 0,001$).

ACKNOWLEDGMENTS

I’d like to thank Dr. Clark, for his patience, wisdom and kindness throughout my studies. I’d like to thank McGill University and the Bioresource Engineering department as well as my family for their support and encouragement. A special thank you to Cloé Rainville, may she always bless me with her grace and love. Finally, my father for his endearing love and courage.

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LIST OF ABBREVIATIONS AND SYMBOLS

AES	Air exchange system
D	Diameter of pipe (m)
f	Friction factor
H_f	Head loss due to friction (m)
HRS	Heat redistribution system
L	Length of pipe (m)
μ	Viscosity ($N*s*m^{-2}$)
MC	Moisture content
MPN	Most probable number
ρ	Density (kg/m^3)
Re	Reynolds number
SAS	Statistical analysis software
TMECC	Test methods for the examination of composting and compost
TS	Total solids (g)
V	Velocity (m/s)

1. INTRODUCTION

Composting is the aerobic decay of organic matter. For centuries, this process has been used to increase soil fertility, reduce organic waste volumes, and more recently, to treat contaminated soils. The process should result in a dark, fully-cured, and humus-like final product, all of which has attained the high temperatures required to destroy pathogenic organisms. The heterogeneous nature of composting ingredients can lead to the presence of anaerobic pockets during composting which emit volatile fatty acids, methane, hydrogen sulfide and other gases that are the source of unpleasant odors. The application of compost to land as fertilizer reduces nutrient losses because nutrients are in a less soluble mineral form, compared to un-composted organic wastes. Moreover, compost improves soil quality and can therefore be useful in land reclamation (Herrmann, 1997).

The primary objective in this study was to test the effectiveness of a heat redistribution system (HRS) in a compost vessel, shown in Figure 1, to transfer heat throughout the compost media and permit uniform composting, resulting in a fully-cured final product. The secondary objective was to test an air exchange system (AES) that would reduce heat loss from the top aeration hole of the compost vessel.

The main design constraint for the heat redistribution system was that no external inputs of energy were to be used. The system would transfer heat from the warmer center of the compost bed to the cooler areas at the outside and bottom of the bed. Once composting began, the temperature of the water inside the heater core would rise, and buoyancy effects would cause the water to flow through the copper tubing to distribute the core heat throughout the compost. Heat was also redistributed by conduction along the copper tubing.

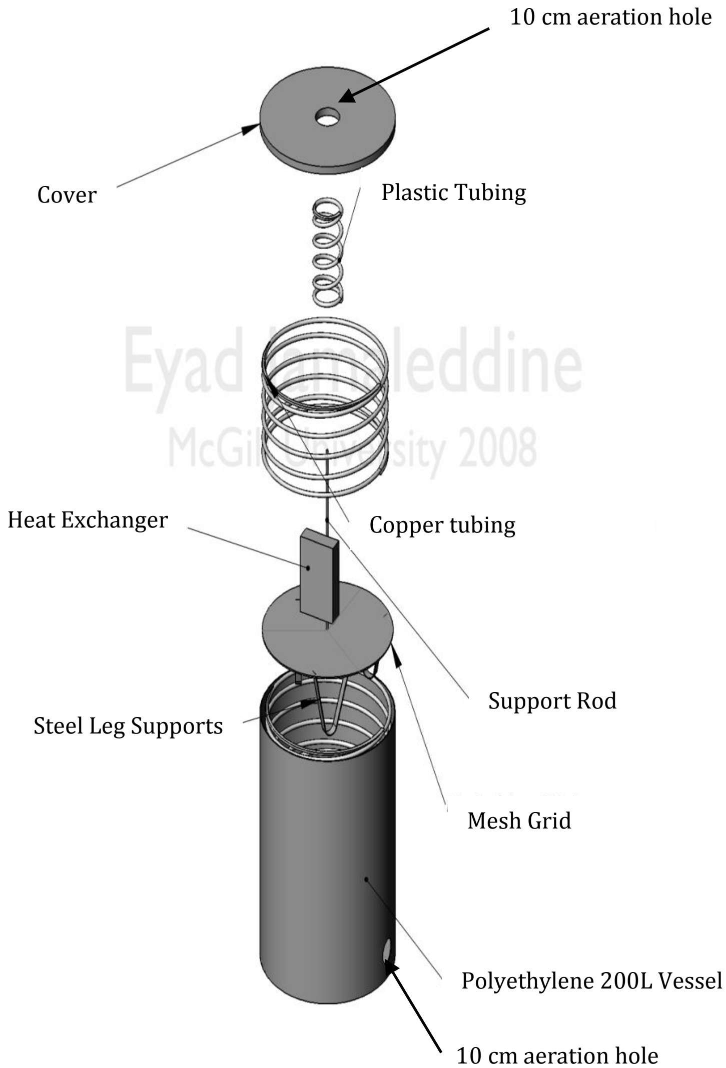

Figure 1: Drawing of the heat redistribution system

2. LITERATURE REVIEW

Precise descriptions of the biochemical changes that occur during the complex process of degradation are unfortunately still lacking (Polprasert 2007). Composting is carried out by successive populations of mesophilic and thermophilic microbes. The end products of this biological metabolism ideally include carbon dioxide, nitrite, water and heat (Polprasert 2007). The main advantages of composting are waste stabilization, pathogen inactivation, nutrient management, and soil improvement (Herrmann 1997).

Biological reactions that occur during composting convert the putrescible forms of inorganic wastes into stable, inorganic forms that are less likely to cause pollution effects if discharged onto land or into water bodies. The biological processes within the degrading material produce heat that can attain temperatures of 55-70°C or more. Such a temperature range, if maintained for at least three days, is sufficient to inactivate the majority of bacteria, viruses and helminthic ova (Polprasert 2007).

The phases of the composting process are distinguished by temperature patterns and changes. The first is the latent phase, corresponding to the time that is required for the microorganisms to acclimatize in their new environment and then to colonize the composting mixture. A growth period follows, dominated by the mesophilic organisms, which ferment the substrate at temperatures between 25-40°C (Herrmann and Shann 1996). The temperature then rises during the thermophilic phase (50-65°C), allowing for waste stabilization and pathogen destruction. If the temperature exceeds 65-70°C, the actinomycetes, fungi and most bacteria are inactivated.

Maturation, also called curing, is the final phase of composting. During this stage, temperature gradually decreases to ambient levels. A secondary degradation takes place which favors humification, the transformation of more complex organic substances to humic colloids and minerals, and finally to humus. During this phase, actinomycetes remain and the fungi reappear along with cellulose-decomposing bacteria. As the temperature continues to decline, actinomycetes become the dominant group, giving the surface of the compost heap a white or grey appearance. Nitrification reactions also take place in which ammonia, a by-product from the waste stabilization phase, is oxidized to nitrite and subsequently nitrate (Polprasert 2007). Some nitrogen is lost in the form of NH_3 emissions (Martins and Dewes, 1992).

Nutrient balance is an essential parameter for an efficient composting process and is characterized by a ratio of carbon to nitrogen, or C/N ratio. If this initial ratio is greater than the optimum value, an excess of carbon is observed, causing growth limitations for the microorganisms and resulting in a longer, less efficient compost process. On the other hand, if the C/N ratio is below the optimum value, then excess nitrogen will be lost to ambient air as NH_3 gas. This results in a loss of valuable nutrients, and oxygen will be consumed too quickly, causing numerous anaerobic pockets. A C/N ratio of 30 is usually considered ideal (Kutz, 2009).

Moisture content in the compost mixture is another critical parameter. Optimum moisture content is important for the microbial decomposition of the organic waste since water is essential for the cell protoplasm and solubilization of nutrients. Insufficient moisture can cause the inhibition of biological processes. On the other hand, an excess of water will cause excessive leaching of nutrients and pathogens from the compost heap and may block the air passages necessary for aerobic conditions. An ideal moisture content ranges between 50-70% (Polprasert 2007).

The structure and particle size of the compost pile is also a key factor in a successful compost process. Degradation of the compost heap is enhanced when the particle size of the materials to be composted is as small as possible, since bacteria, fungi and actinomycetes may more easily decompose them. However, the same does not apply to the bulking agents that must be added to raise the C/N ratio. Bulking agents are not only used as a means to raise the quantity of degradable organic carbon, they provide structural support to the compost pile and increase the number of air voids within the pile. Maintaining air space in the compost mixture is critical to proper aerobic digestion of the organic wastes. Examples of such materials include: sawdust, wood chips, shredded paper, straw, rice straw, peat, and rice hulls.

Guidelines for compost quality with respect to health and safety have been established in Canada by the Canadian Council of Ministers of the Environment (CCME, 2005). Based on the end use of the compost material, two compost categories, “A” and “B”, have been developed. Category A indicates unrestricted use and can be used in any application, such as agricultural lands, residential gardens, horticultural operations and many more. Compost that has restricted use belongs to the category B because of the presence of sharp foreign matter or high trace element content.

Moreover, compost must be mature and stable at the time of sale or distribution. To respect such requirements, the compost must have been cured for a minimum of 21 days and meet one of the following three restrictions:

1) Respiration rate is less than, or equal to, 400 mg of oxygen per kilogram of volatile solids per hour;
2) Carbon dioxide evolution rate is less than 4 mg of carbon per gram of organic matter per day;
3) Temperature is less than 8°C above ambient air.

Additionally, pathogenic organisms in the compost may pose a risk to human health. To reduce these health risks, the material must be maintained at operating conditions of 55°C or greater for three days if an in-vessel composting method is utilized. Another method to ensure public safety is a fecal coliform count, which must be lower than 1000 MPN (most probable number) per gram of total solids.

The main hindrance of the compost process is the uneven temperature distribution throughout the mass, resulting in incomplete inactivation of pathogens. Another is the difficulty of obtaining a mixture where solely aerobic digestion occurs, without pockets of anaerobic composting. Heat generated by the compost mixture is fundamental to maximize decomposition rates and to produce an end product that is safe and free of harmful pathogens.

3. AN IDEAL COMPOSTER

While composting occurs naturally, it can be accelerated by human intervention. As mentioned previously, four factors are primary in maintaining an efficient composting process: temperature, humidity (moisture), aeration and nutrient balance. The design of an ideal composter would address three of these parameters through mechanical or electrical implements, and the last one, nutrient balance, would be managed through educational means, such as a pamphlet that would indicate the proportions of organic waste to be added as well as how much bulking agent may be required for different categories of organic waste (Polprasert 2007). Another important factor when dealing with domestic composting would be odor control. Odor management is primordial when composting is done in proximity of residential areas. It is important to note that some of the elements suggested below, although pertinent to the notion of an ideal composter, might not comply with the proposed concept of an energy independent composter.

Temperature

Heat is generated by the microbial digestion of the organic waste, but it can also be added to the compost mixtures by means of a heating element. To do so, the element could be placed in the center of the vessel, along the central rotational access. Fitted with a temperature sensor, the heating element could keep the mixture of organic matter at minimal temperatures, say 30°C during cold conditions, to maintain the bacterial process (Polprasert 2007).

Humidity (moisture content)

Moisture content is indispensable for microorganism growth, due to water being a medium through which nutrients are dissolved. Therefore, low moisture content reduces microbial activity and slows down the decomposition process. Ideal aerobic decomposition, as mentioned above, occurs between 50 and 70% moisture content (Hermann, 1997).

For the building of an ideal composter, moisture content must be addressed. To do so, an indicator of moisture content of the composting mixture, a sensor, must be installed within the vessel. This indicator could have a readout placed conveniently on the vessel, where the user is able to determine the amount of water that needs to be added to the mixture when filling the batch composter. Although the indicator is fixed, the vessel could have one or multiple latches that fix the vessel in place when it is not rotating, this would ensure that when stationary, or latched in, the indicator would be upwards and readable (Hermann, 1997).

Aeration

To maintain aeration, a combination of vents and a tumbler mechanism can be added at different sections of the composter, ensuring a constant flow of fresh air into the organic media. If manual aeration is desired, the composter could be set on a shaft and the user could rotate it during the fermentation process to avoid the formation of anaerobic pockets of microbial digestion. Aeration ports could be placed at the extremities of the vessel to permit air flow from one end to the other. If passive aeration is deemed not enough, one could place a variable speed fan at one extremity of the compost unit. This fan could have two settings and, depending on the amount of compost within the vessel, the user could set the fan to the high or low setting (Hermann, 1997).

Nutrient Balance

The material introduced into the vessel must have the proper balance of carbon and nitrogen. This is an important part in ensuring that the composting process occurs properly, attaining the thermophilic phase and retaining nutrients past the curing phase. A plastic chart could be placed on the side of the vessel, the user could refer to that chart and determine the amount of bulking agent that should be added to the vessel in relation to the food or garden waste that is to be composted. Such a chart should be in kilograms and volumetric readings could be marked on the side to facilitate filling of the composter, considering that users tend not to weigh their organic waste. Alternatively, the composting unit could be sold with a filling pail that contains a graduated scale of varying volumes on the side to facilitate measurements for the average user (Hermann, 1997). Other factors to be considered would be the construction materials of the vessels, different automation systems for heating, and rotational mechanisms.

The purpose of the design described here with the HRS and AES was to deal with heat requirements mentioned above, without external inputs of energy. Therefore, a system that would utilize the available heat emitted by the compost heap and redistributed in a manner that would better the overall degradation process throughout the vessel. This is key in maintaining a uniform compost mixture and keeping the compost at different segments of the vessel at the same phase.

Overview of Current Composting Implements and Practices

Statistics Canada refers to the composting process as one method of diverting of waste from local landfills. It is stated that the average Canadian sent 51 kg of organic waste to composting facilities in 2004, compared to 32 kg in 2000 (Statistics Canada, 2008). This increase in volume indicates a rise in composting knowledge and the public's willingness to participate in the proper disposal of organic waste.

Organics also occupy an increasing share of total materials diverted. In 2000, organics made up 16% of all materials diverted from disposal. By 2004, approximately 21% of total weight was composted. Even more so, an in-depth analysis through rigorous surveying and data gathering seemed to suggest that composting was slowly becoming a more popular activity in Canadian households. According to the Households and the Environment Survey in 2006, 27% of households utilized the process of composting to deal with a portion of their organic waste in comparison to 23% in 1994, an increase of 4% (Statistics Canada, 2008). Bearing in mind the increased awareness to environmental issues, it can be assumed that interest in organic waste management on a local level is also growing. Moreover, the province of Quebec is taking on a policy to ban organic waste from landfills as early as 2020 (MDDEP, 2012). This policy involves a domestic and centralized organic waste management initiative. Municipalities are presently establishing regulations and guidelines for domestic composting. According to the Quebec Ministry of Sustainable Development (MDDEP, 2012), these regulations are put in place to avoid poor practices and alienation of the general population towards composting. The document also establishes goals for organic waste management. For example, municipalities, such as Longueuil, have set a goal that by the year 2016, 60% of organic waste should be dealt with through centralized and domestic composting (Gorrie, 2012). The banning of organic waste from landfills and other municipal regulations promoting composting are all factors to be considered when evaluating the need for an effective domestic composter. With implementation of such regulations, composting will continue to gain popularity.

Patents

Numerous composter patents have been filed. A good example is that of Seymour (2000; Fig. 2. This composting device is labeled as a rotary composter having a cylindrical vessel. The vessel is divided into multiple compartments, including an inlet compartment, a discharge compartment, and multiple intermediate digesting compartments. The drive mechanism is powered by a variable speed motor, linked to the main shaft of the vessel. Air is forced through the vessel by a variable speed fan. This patent was filed in 1998 and made public in 2000. Figure 2 depicts a central rotating shaft with baffles, to push the compost from inlet to the outlet (Seymour, 2000). Note that Seymour (2000) does not specify what materials are to be used.

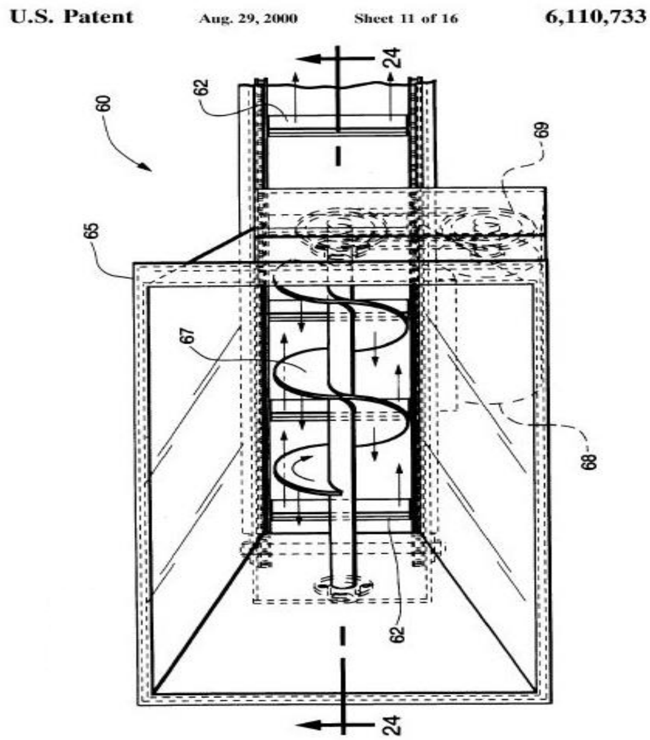

Figure 2: Rotary composter with a central shaft and baffles built to push compost from the inlet to outlet (Seymour 2000).

Another design involves a similar cylindrical construction (Raghunathan, 1994). This domestic composter has a tapered body comprising of an upper and a lower half. It is stated in the patent application that the top half has a ventilation system that permits airflow. The application suggests that one can fully disassemble the unit for better transportation when produced industrially. It also indicates that the multi compartment design allows for better ventilation than conventional cylindrical composters, due to the shape of the unit (Fig. 3). Insulation is not mentioned in the patent application. The patent however suggests that the composter is to be built of plastic, no heating or forced ventilation systems are mentioned.

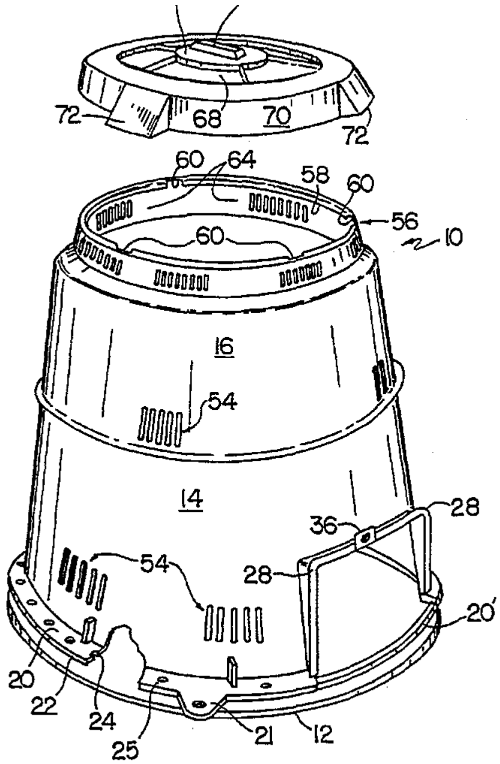

Figure 3: Tapered, cylindrical domestic composter (Raghunathan, 1994).

Masse (1995) suggests that a sphere-shaped composting unit provides the ability to roll the composting unit on a level surface, facilitating the mixing process and encouraging users to mix the organic matter more often. He proposes that the unit be kept on the ground and filled through a removable section in the sphere (Fig. 4).

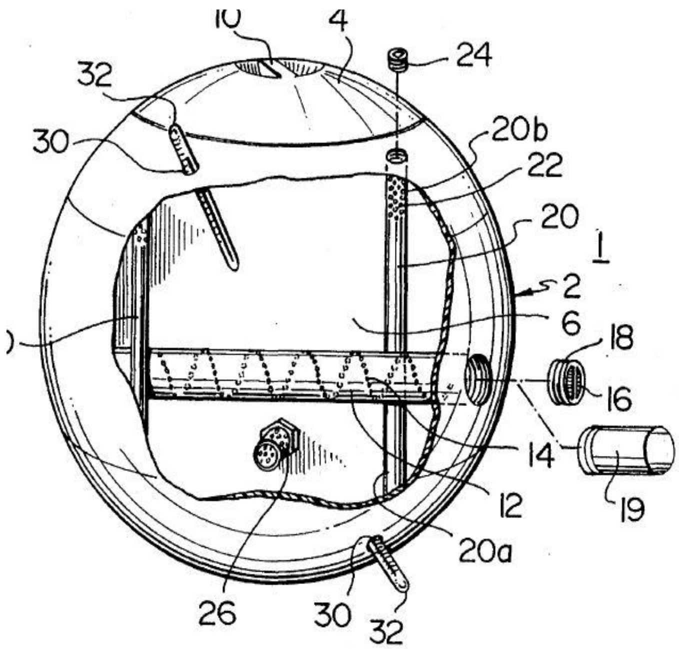

Figure 4: Spherical domestic composter (Masse, 1995).

Items 16, 26 and 20b in Figure 4 depict air vents in the vessel. These have plugs that can be removed to clean the perforated cylinders, ensuring the flow of air and that no debris remains lodged in the air vents. Seal 18 has a screen to allow airflow into the empty cylinder. Items 32 and 30 are opening for thermometers to monitor composting. These openings can be plugged when the thermometers are removed. The sphere is made of polyethylene, but Masse (1995) suggests that it could be made of a 5 mm thick stainless steel material. One should take into consideration that municipal regulations in some areas, such as the city of Quebec, prohibit the installation of a composting unit directly on the ground to avoid rodents and other wild animals from accessing the waste (MDDEP, 2012). Also, this system does not seem to have odor control measures to ensure that the composter does not become a public nuisance. Due to its spherical shape to facilitate the mixing of compost, the design (Fig. 4) must be placed on the ground, which, as mentioned above, is not tolerated in many areas. Even more so, neither of the composters in Figures 3 or 4 have a built-in heater or insulating material to maintain the composting process in cold weather. This can be an issue in northern climates. Filling and emptying either of the composters above can be a nuisance considering they would be placed on the ground. The spherical unit may be turned with the lid off. However, even though the patent does not suggest a size for the sphere, one could assume an overall weight of over 40 kg when full, hence emptying this unit could be a nuisance.

Other patents include a frame to hold the composting vessels (Cook, 1994). This complies with Quebec regulations (Fig. 5).

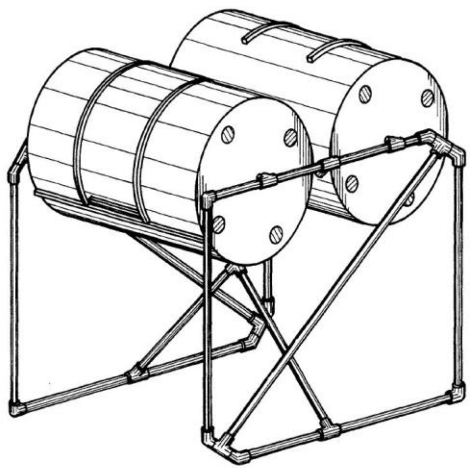

Figure 5: Isometric view of double-barrel composter, sitting on their frame (Cook, 1994).

The system described in Figure 5 has eight air vents per vessel, permitting air flow through the compost. The vessels are placed on rotating central shafts for mixing purposes and can be filled through the side ports. Although the material of fabrication is not specified in the patent report, one could assume plastic would be used. The vessels are to be set 1 meter from the ground, sitting on a steel frame. Although this system addresses mixing, aeration and suspension frame issues, it does not include a heating element or insulation materials to reduce heat loss (Cook, 1994). This is a serious issue that could compromise the performance of the composter in cold weather.

Richards (1974) patented the design of a rectangular unit mounted on a perforated pipe extending axially through the container (Fig. 6). A water holding manifold is connected through a conduit to the perforated pipe. Water vapor is carried from the manifold by means of air which is introduced into the manifold through a vertical pipe. The wet air passes through the perforated pipe and into the container, providing adequate moisture and air for the composting operation. A mechanism is also provided to rotate the container and to hold it at a pre-selected angular position (Richard, 1974). The patent file states that the system uses wood as an insulation material to prevent heat loss.

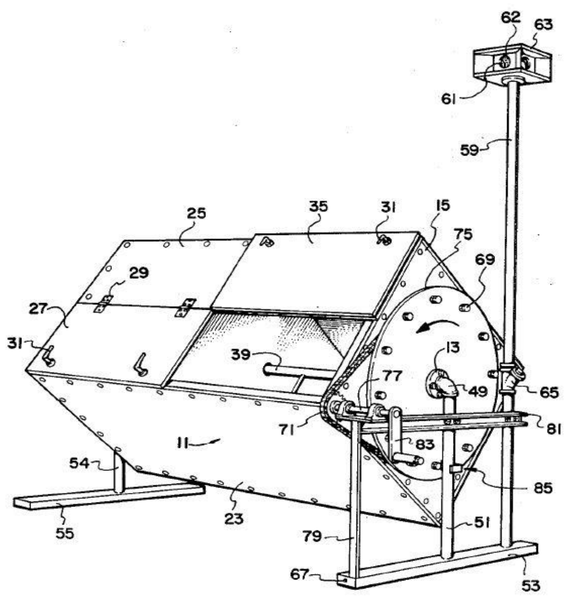

Figure 6: Rectangular, rotating composter (Richards, 1974).

Although this patent was filed over forty years ago, assuming the heating mechanism works, it does meet heating, rotational and suspension requirements. Ventilation ports are not mentioned in the patent filing.

Having looked at various patents, one that had some similarities to the design proposed here, with the heat redistribution system (HRS), was that of Morisson (2007). The stated objective of this patent is the dissipation of the heat throughout the vessel to maintain good composting conditions, as well as the ability to provide air for aerobic decomposition. The invention is a composting apparatus with an air inlet in the container to provide air to the composting materials (Fig. 7). “The heat transfer device is comprised of a coil located within the container and which, when the container is supplied with compostable materials, is embedded in the compostable material, the coil containing a fluid so that when decompositions occurs, the heat generated forces the liquid to flow throughout the compost media” (Morisson, 2007). Note that this system does not use a heat exchanger and the specifics of the design are not discussed in the patent application.

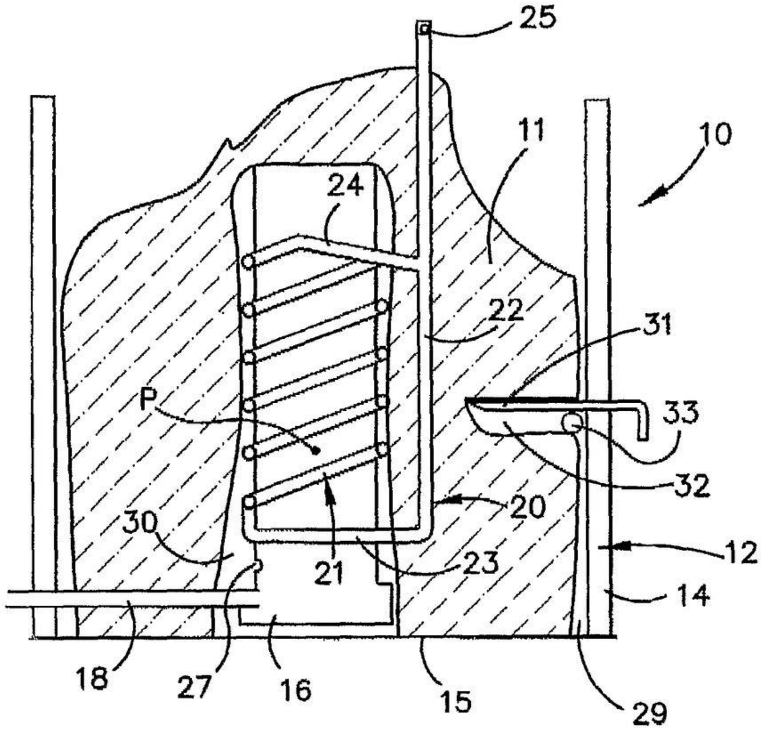

Figure 7: Composter including a coil to redistribute heat throughout the compost bed (Morisson, 2007).

Patent Assessment Conclusion

The patent assessment indicates that none of the described compost units meet the ideal compost requirements described in the previous section. Most designs included the use of various types of plastics as the main material to build the barrel containing the organic waste, thus avoiding corrosion issues. However, vermin could easily chew through the outer plastic covers of composters. This issue should be considered when building an ideal composter. A thick outer wall could be used. An analysis of heat redistribution, heat loss, the choice of materials used, along with a ventilation efficiency evaluation could be done for each composting system described above to determine the most efficient setup is desired, but it has already been established that there are serious flaws to these designs.

It is also important to mention that according to Quebec municipal regulations, composters cannot be directly placed on the ground. Therefore the first three patent e designs, by Seymour (2000), Raghunathan (1994) and Masse (1995), would not be a valid design for Quebec (Ville de Québec, 2013).

The design of any composter should take into consideration heating, moisture content and aeration, which was not applicable to the patents described above. Also, none of the above patents mention important factors such as nutrient balance, carbon to nitrogen levels and the type of waste to be composted. In addition, none of the product descriptions offered guidance on bulking agents to give the compost more structure. Note that the above patents were picked to attempt to cover the various shapes for composter design: spherical, rectangular and cylindrical shapes. Considering the general analysis of existing patents, the process of composting analyzed in the literature review section and the ideal composter guidelines, it is now possible address the issues and present an improved composter.

It is important to note the difference between small scale composters where energy inputs might be acceptable and larger, stationary, very low-maintenance composting units. Small scale composters refer mostly to residential units that require electricity and devices small enough to fit on a kitchen counter or in a garage; whereas much larger units would include methods where the organic material is left in a heap outside and rotated once in a while. The design presented in this paper, as well as some the patents described, may be categorized in a section that lies between the two extremes. Although the design presented in this thesis ranges in the smaller scale, the goal is for it to be autonomous and efficient, hence requiring no human manipulating throughout the compost process and no external inputs of energy.

The objective of the patent search section was to gain general knowledge of available composting implements and their designs; however the present text will focus on a passive design system, where no inputs of energy are required. Based on the information acquired concerning the ideal composting parameters, a new approach will be discussed. The concept is centered on the fact that the composting unit does not require external energy inputs nor does it require manual maintenance and this will be accomplished by designing and implementing a heat redistribution system (HRS) and an air exchange system (AES). Unlike the compost designs described in the literature review, this design is more suitable for a commercial setting than a residential one.

To determine whether the designed systems provide better performance than a regular unit, time to reach maturation, faster temperature rise and temperature differences within the same vessels were observed.

4. MATERIALS AND METHODS

Summary of Protocol

Composter vessels were equipped with heat redistribution systems or air heat exchangers, and experiments were run to compare the performance of these composters with control vessels that had neither apparatus. The experimental design involved running twelve vessels simultaneously. Four were fitted with the HRS, four with the AES and four were controls. To determine the effectiveness of the HRS and AES designs, all the vessels were fitted with three K-Type thermocouples located at 33, 54 and 84 cm from the bottom of the vessels. The thermocouples were connected to data loggers (Agilent 34970A, Agilent Technologies, Santa Clara, CA) that took readings of the temperature every twenty minutes. The temperature readings showed whether the systems were properly redistributing the core heat of the compost mixture throughout the vessels. Respirometry analysis was done to determine the maturity of the compost throughout the 65 days of the experiment. The top and middle of the compost bed was sampled five times, starting on day 1 and every two weeks thereafter until the end of the experiment (Thompson et al., 2002). Samples were placed in plastic, sealable bags and put in a refrigerator set a 4°C for 24 hrs. They were split into different portions to be used for respirometry, moisture content analysis, total solids content analysis, and C/N analysis, which were conducted according to the test methods for the examination of composting and compost (TMECC) guidelines (Thompson et al., 2002). The samples to be used for respirometry were placed in Erlenmeyer flasks with rubber stoppers and incubated at 80% humidity and 38°C for 12 hrs. After incubation, the samples were placed in a water bath and kept at 30°C while air was re-circulated through each of the beakers using 0.635 cm plastic tubing connected to each flask holding the samples. This process was used to oxygenate the samples. Afterwards, air samples were taken with syringes from each of the sealed beakers every twenty minutes for 90 minutes, as described in the "Respirometry" section. This permitted the measurement of the oxygen consumption rate within each of the samples, and therefore the maturity of the compost.

Heat Redistribution System Design

The heat redistribution system consists of copper tubing, plastic piping, a heat exchanger, and a metal grid to support the compost (Fig. 8). To build the system, the size of the copper tubing, the size of the plastic piping, the type of heat exchanger and the size of the metal grid to support it all were determined. To do so, a few factors were considered: thermal driving, friction in the pipes and velocity of the of the water flow, depending on the type of heat exchanger chosen. All fittings and the support grid used were either stainless steel or treated with oxidation retardant paint. As can be seen in Figure 8, the heat exchanger was placed at the center of the structure. The system is filled with water and a release valve at the top of the plastic tubing is used to release trapped air in the system. The metal mesh was composed of steel coated with inorganic galvanized zinc with a mesh opening of 2.25 cm (1 in.). The metal grid was placed at the bottom of the system was used to support the organic waste 0.203 m (8 in.) from the bottom of the 200 liter polyethylene vessel. This was key in maintaining airflow in vessels, as the air would come in from the bottom of the barrels 10.16cm hole (4 in), seep through the composting heap and flow out of the top 4-inch diameter hole. As mentioned previously, the objective of the HRS was to redistribute the core heat within the composting vessels to the outer edges of the compost mixture. This would essentially accelerate the latent phase and activate the microorganisms that lead to the mesophilic phase. The HRS design depends on buoyancy and convection, therefore all piping was designed to maximize water and heat flow. To design the piping system, friction in the pipes and thermal driving had to be considered. Proper sizing allowed for water flow throughout the pipes while maintaining a small enough HRS design to fit within a 200 L polyethylene vessel.

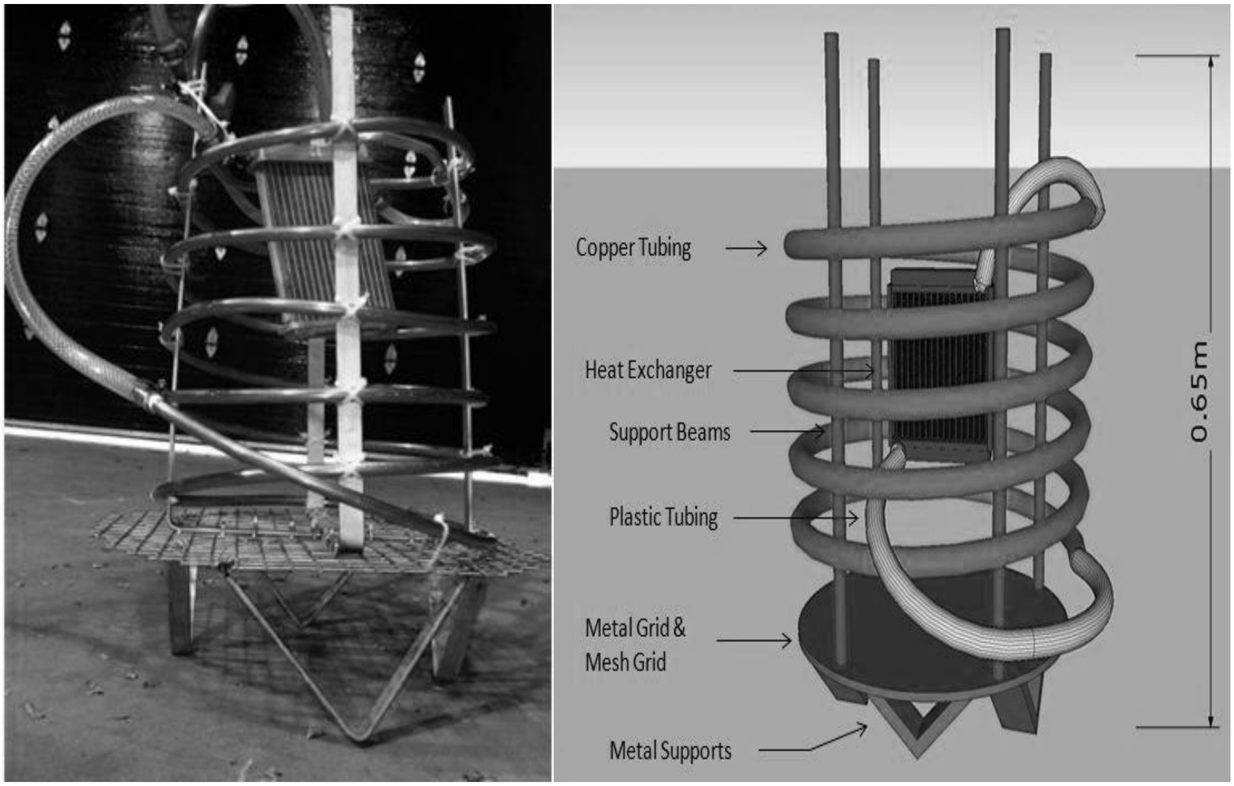

Figure 8: Photograph and schematic drawing of the Heat Redistribution System.

Thermal Driving

Thermal driving head is the force that causes natural circulation to take place. It is caused by the difference in density between two volumes of fluid. When two volumes are at different temperatures, the volume with the higher temperature will have a lower density. The difference between the forces of gravity exerted on the two volumes will cause the warmer fluid to rise and the colder fluid to sink (Munson et al., 2005).

The continuous warming of the barrel is based on the following principle. As the microorganisms within the compost bin begin to digest the nutrients, heat will be dissipated and once it has elevated the temperature of the water in the recirculation tube, the warmer water will slowly rise as the cold water spirals down the copper tubing towards the bottom of the barrel. The water in the heat exchanger will be warmed quicker than the water in the copper piping due to its proximity to the center of the vessel. This will drive warmer water from the center of the vessel to its extremities.

Friction in the pipes

Two factors were considered when calculating the friction loss in the tubing: the Reynolds number and consequently the head loss due to friction. The Reynolds number is necessary to determine whether the flow is laminar or turbulent, and head loss due to friction is necessary to establish the losses in the system due to the choice of material.

$$Re = \frac{\rho \cdot V \cdot d}{\mu} \quad (1)$$

The temperature of the water within the heat redistribution system will ideally remain around 55°C.

ρ = 985.7 kg/m^3

μ= 5.067 E-4 N*s/m^2

d= 0.5 in = 0.01905 m

V= 0.01 m/s

A velocity of 0.01 m/s was assumed and a resulting Reynolds number of 370 was obtained, which describes a laminar flow.

The relative roughness coefficient is determined by the ratio of the roughness factor (K_s) divided by the diameter of the pipe. Following Munson et al. (2003), the roughness factor for a copper pipe is 0.0015 mm and the diameter of the pipe was 0.01905 m. This yields a relative roughness coefficient of 0.000236. The equation describing head loss due to friction is the following (Equation 2):

$$h_f = f \cdot \frac{L}{D} \cdot \frac{v^2}{2g} \quad (2)$$

Where:

v is the average velocity: 0.01 m/s

L is the pipe length: 4.0 m

D is the pipe diameter: 0.01905 m

f is the friction factor: 0.52

Having established a laminar flow due to the low Reynolds number obtained above, the friction factor is defined as 64/Re. Calculations based on the equation for head loss due to friction (Equation 2) gave 5.57 $x10^{-3}$ m. Therefore, this sizing of piping and length of piping could be used without having to worry about friction impeding flow throughout the copper tubing.

To support these theoretical findings, experiments were conducted in the lab, where only the inner structure of the compost unit was used, as seen in Figure 8. Heated water (50°C) colored with blue dye was then inserted into the system and bubbles were removed using the release valve. The blue color permitted visual confirmation that the fluid was moving through the system, without external inputs of energy.

Air Exchange System

It was noticed in preliminary experiments with the HRS that there was significant heat loss through the top 10.16 cm (4 inches) hole. To mitigate the loss of heat from the top of the vessel, a concentric-tube heat exchanger was designed. The system was built using two galvanized tin tubes, one of 0.1 m diameter and the other of 0.15 m diameter. The inner tube extended down past the top hole into the vessel, resting 0.2 m from the bottom of the vessel on the metal grid (Fig. 9).

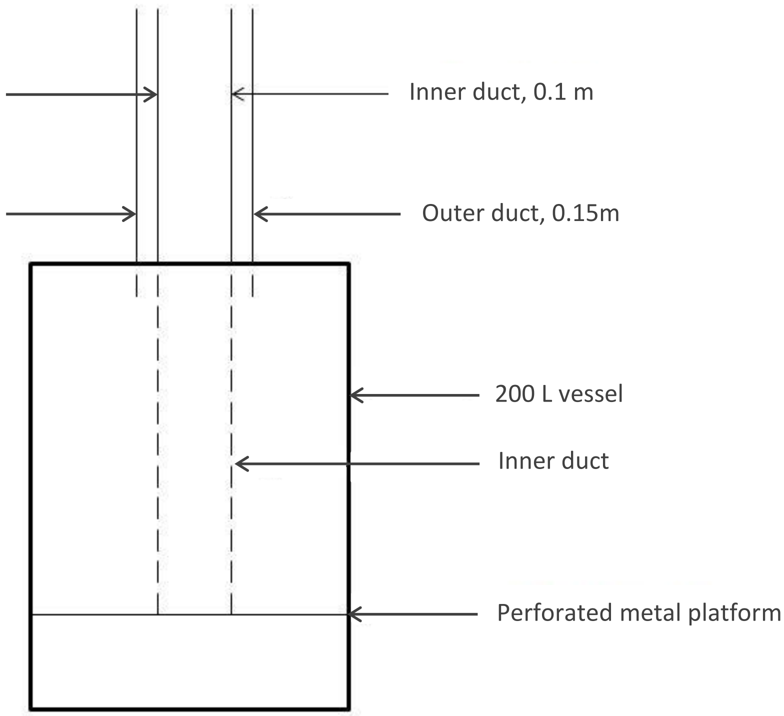

Figure 9: Air exchange system, cut-out side view, installed in vessel.

To determine the size and length of the heat exchanger, heat transfer calculations were done. Considering warm air tends to rise, due to its lower density, it would flow through the larger tube upwards, lowering the air pressure within the vessel. This would be compensated, through convective air flow, by ambient air flowing downwards through the central tube to the bottom of the vessel. Through heat transfer between the larger and smaller tubes, this would permit air flow through the compost heap, while reducing heat loss from the top 0.15 m hole. Figure 10 depicts air movement through the heat exchanger.

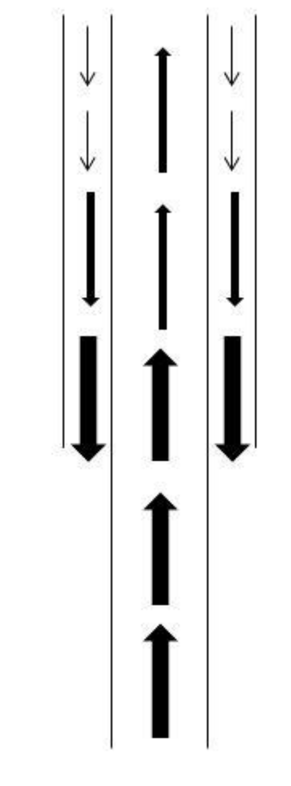

Figure 10: Arrows indicate the direction of airflow through the concentric tubes of the air heat exchanger. Thicker arrows indicate higher temperatures.

To calculate the length of the piping, uniform temperature gradients and uniform air velocity were assumed. Assuming the minimum temperature levels suggested by the TMECC guidelines for curing compost (Thompson et al., 2002), a 55°C temperature was assumed for the center of the compost media and an ambient temperature of 14°C was assumed. Sample calculations are included in Appendix B. It was initially assumed that the difference in temperature between the exhaust air at the outlet of the air exchanger and the inlet ambient air at the top of the air exchanger would be 3°C, but that led to a 3 meter long pipe. For practicality, a drop of 10°C between the interior temperature and exterior temperature was deemed sufficient. Therefore, tubing length protruding from the top 0.10 m hole would have to be of 1.25 m, as shown in Figure 11.

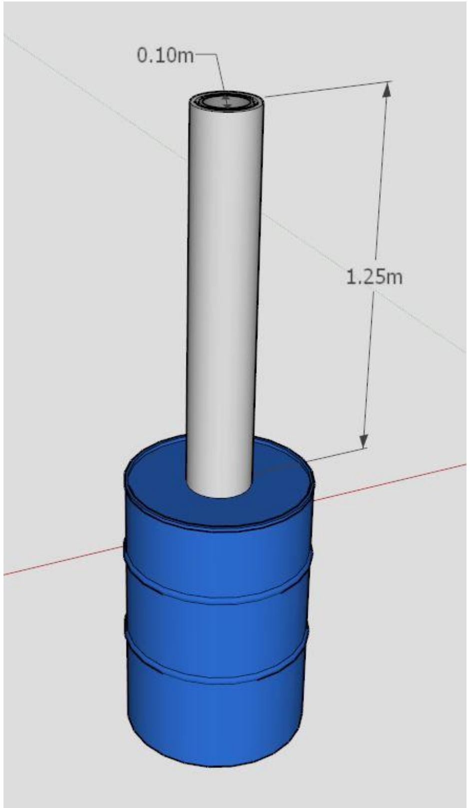

Figure 11: AES piping protruding 1.25m out of the vessel top, 0.1 m diameter.

Homogeneous Compost

Dog food (Purina Dog Chow®, Saint Louis Missouri, United-States) was chosen over manure as the primary compost ingredient chiefly for its uniformity. Another beneficial aspect of dog food is its high water absorption capacity. In order to determine the total mass of compost materials, a volume and density had to be established. The height of compost bed was 0.66 m and the diameter of the 200-litre polyethylene barrel was 0.53 m. From this information, the volume of compost material per barrel was estimated to be 0.15 m^3. The density of the mixture was estimated at 550 kg/m^3 (S. Barrington, McGill University, personal communication, 28 October 2010) yielding a total mass of 82.5 kg. Approximate masses of dog food, wood chips and water were determined to acquire the necessary quantities of each. Assumptions were also made concerning the total solids and volatile solids of the materials. However, the actual values for density, total solids (TS), moisture content (MC) and ash content were measured once the materials were purchased.

Compost Mixture Recipe

The protocols used to determine the compost mixture were done according to the TMECC guidelines (Thompson et al., 2002). Assumptions for total solids and ash content for dog food and wood chips were respectively 84.3% and 9.7% (Nakasaki et al., 2002), and 90% and 5% (Polpraset, 2007). From these values, the percentage of carbon and nitrogen were found (Table 1) using C/N ratios of 18 for dog food and 142 for wood chips (Phillip, 2009). The amount of carbon present in every kg of dog food and every kg of wood chips was then determined and these figures were used to determine a mixture with the desired C/N ratio of 30. Final masses of 36 kg and 32 kg were obtained for dog food and wood chips, respectively, per composting barrel. A total of 12 barrels were prepared, with three different treatments, including heat redistribution systems, air heat exchangers and the control compost vessels, with four replicates for each treatment.

Table 1: Physical properties of compost ingredients (estimated from Phillip, 2009)

Material	%TS[a]	%VS[b]	%C[c]	%N[d]	C:N	%MC[e]
Dog food	84.3	90.3	49.3	2.7	18	15.7
Wood chips	90.0	95.0	51.9	0.3	142	8.9

[a] TS = Total solids content, [b] VS = Volatile solids as % of TS, [c] %C = Percent carbon in sample, [d] %N = Percent nitrogen in sample, **[e]** Moisture content, wet basis

Since the total mass was approximated to 69 kg, 75 L of water was required to attain an ideal moisture content of 60%. The moisture from both dog food and wood chips accounted for 4.9 L of water (Table 1) and so 70 L of water had to be added to the compost mixture. To ensure that such a large quantity of water would remain within our system rather than leak out through the bottom 4-inch hole, the wood chips were soaked for 3 days in a plastic bin. The amount of water absorption was estimated by placing a marker on the side of the container and determining the difference of height after three days of soaking, but a drying test was done to verify the numbers obtained. In this test, the moisture content of soaked wood chips was determined after drying the sample in an oven and calculating the weight difference before and after the procedure.

Once the materials were purchased, they were analyzed for moisture content, density, percent total solids and percent ash content. To determine the total solids, three samples of each material were weighed, placed in an oven at 103°C for 24 hours and weighed once more. The dried material was then placed in a furnace at 550°C for 5 hours, to determine the ash content. The density of the compost was measured by weighing the samples in a crucible of known volume. Characteristics of the final compost mixture were analyzed in the same manner as the dog food and wood chips, although 6 samples were tested instead of 3. With these results, calculations were verified and iterations were conducted once more to yield more accurate masses of each ingredient, based on measured parameters.

In Table 2, results for mean moisture content, mean total solids content and mean ash content are presented for both dog food and wood chips. The moisture content and total solids content were close to the values that had been initially assumed. The densities were quite different with 341.3 and 162.0 kg/m^3 for dog food and wood chips respectively on a dry basis. Also, the moisture content of the wet wood chips increased from 16.5% to 53.2%, accounting for an additional 6.96 L of water per vessel. Adjusting for the new experimental values, following the methods previously described, new masses were obtained: 23 kg of dog food, 32 kg of wood chips and 36 kg of water. From this mass of water, 5.1 L are initially present in the compost ingredients and the wood chips absorbed an extra 8.5 L. Therefore, only 66.5 L of water had to be added to the mixture.

Table 2: Measured properties of compost materials: total solids, ash content and moisture content

Material	% Total solids (Std. Dev.[a])	% Ash content (Std. Dev.)	% Moisture content, wet basis (Std. Dev.)	Mass of ingredient per barrel *kg*	Mass of water *kg*
Dog food	91.1 (0.30)	6.8 (0.10)	8.8 (0.29)	36	3.17
Wood Chips	83.4 (0.19)	3.9 (0.99)	16.3 (0.18)	32	5.30
			Total:	42	8.47

Statistics are based on a sample size of n=3 measurements.
[a] Std. Dev. = Standard deviation

The 6 samples taken from the final mixture of compost yielded a mean density of 599 kg/m^3 and mean moisture content of 63%.

Maturity of Compost Evaluation

Temperature was used to determine the effectiveness of the heat transfer system and the air redistribution by comparing temperature differences between center, top and bottom thermocouples. To manage the large number of data points, SAS PROC MEANS (SAS Business Analytics software version 9.3, SAS, Cary, NC) was used to determine the daily means. SAS PROC MEANS was also used to evaluate the C/N data to determine whether there was a significant difference between depths of sampling or treatments. Therefore three tests were done independently to measure the state of the compost: temperature, respirometry and C/N ratio.

Temperature

To evaluate the efficiency of the heat redistribution system, K-type thermocouples were placed at heights of 33, 54 and 84 cm from the bottom of each barrel. Calibration curves were made to ensure the thermocouples were accurate (Fig. 12). Appendix A contains the calibration curves for all thirty-six thermocouples.

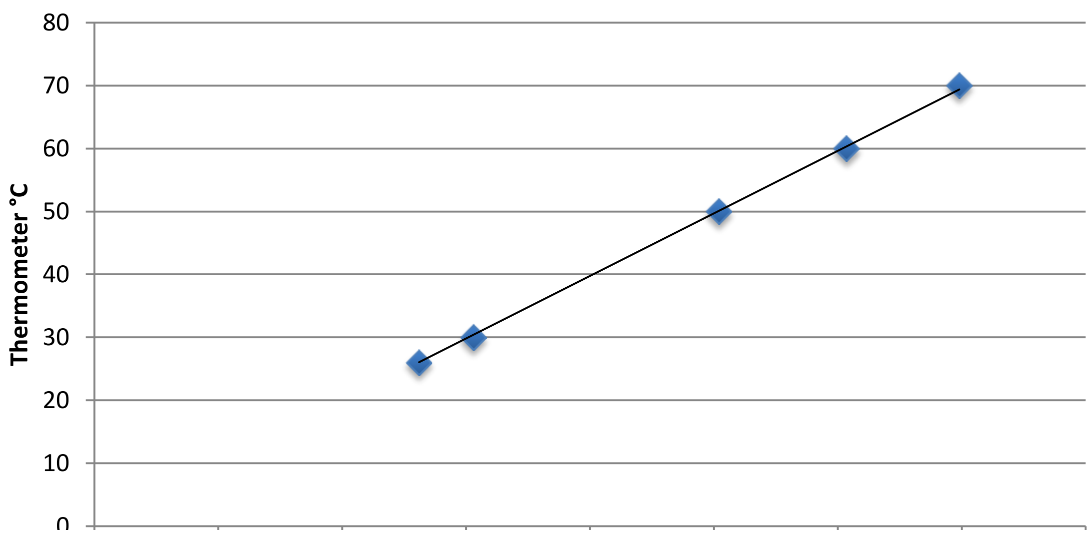

Figure 12: Example of a thermocouple calibration curve where the temperature readings of the thermocouple (channel 101) were plotted against the temperature readings of the thermometer in the water bath.

The overall temperature attained and sustained by each thermocouple would provide the maturity level of the compost. As mentioned earlier in the literature review, between 20-45°C, the composting material would be assumed to be at the mesophilic stage and beyond 45 degrees would be assumed to be at the thermophilic stage (Herrmann and Shann, 1996). That the compost mixture maintain 55°C for over three days is one of the requirements for production of grade A compost (CCME, 2005). By evaluating the temperature data, one can not only determine if the compost attained sufficient temperatures to destroy pathogens and be labeled grade A compost, but also determine the difference of temperature between the different layers of the composting mixture, providing feedback on the function of the air exchange system and the heat redistribution system.

Two Agilent data loggers (Model #: 34970A, Agilent Technologies, Santa Clara, California) were used to acquire the temperature readings from the three pre-determined heights previously mentioned. The data loggers were set to take temperature readings at twenty-minute intervals.

Data were collected for a period of sixty days at McGill's Large Animal Research Unit (LARU) in Saint Anne de Bellevue, Quebec, Canada.

Respirometry

Respirometry was used to determine the maturity level of the compost by measuring oxygen the depletion rate, based on the principal that mature compost will consume less oxygen due to decreased microbial activity. Samples were taken at the beginning of the experiment and then every fourteen days afterwards up to forty days. Twenty-five 500 ml flasks were marked with identifying numbers, nylon mesh disks and aeration tubes were inserted into the flasks, and their tare weights were recorded. Two, 300 mL samples (Fig.14) of raw compost were stored in re-sealable plastic freezer bags for each vessel. One sample taken from the top of the vessel and one taken from the bottom, as depicted in Figure 14. The samples were then incubated for 28 hr at 34°C and a relative humidity of 99%. The bags were covered with a damp cloth to minimize moisture loss. All samples were checked every 8 hours for signs of anaerobic conditions. After incubation, the samples were divided into two aliquots of 250 cm^3 and 50 cm^3 (Thompson et al., 2002).

Specific oxygen uptake rate

In a 250 ml beaker, 50 ml of distilled water was added to the 250 cm^3 aliquot of compost. The mixture was then poured into a 500 ml flask and the weight and mass of the filled flask was recorded. The flasks were weighed down using weight rings and placed into a 34°C water bath containing 6 cm of water (Fig. 13) (Thompson et al., 2002).

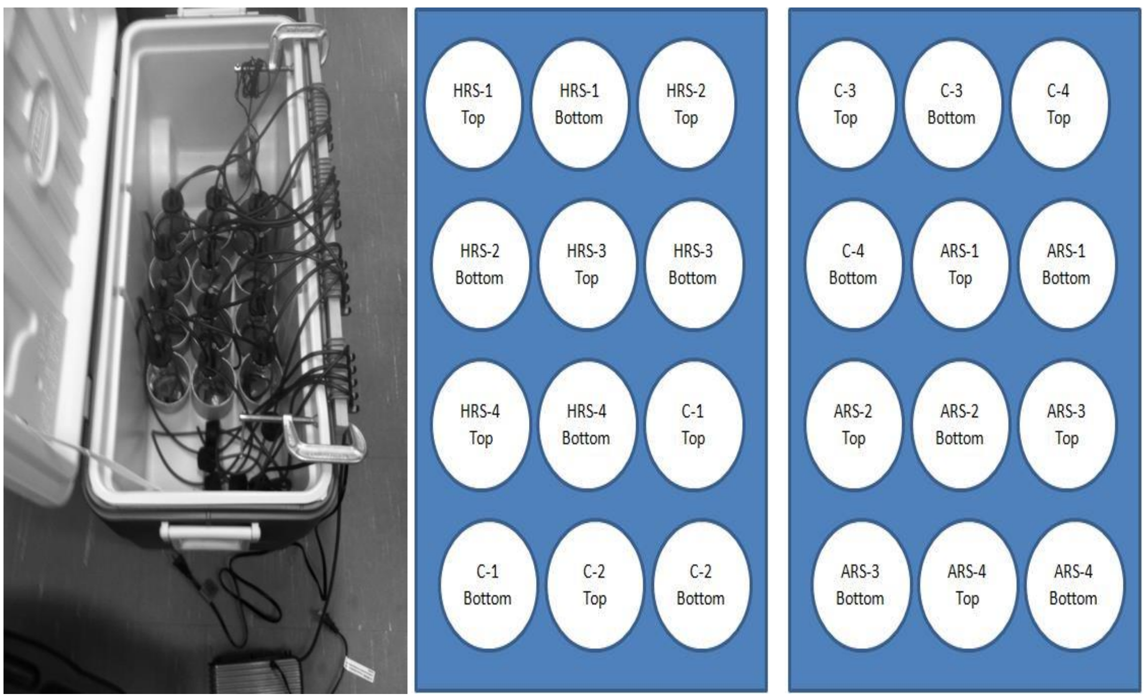

Figure 13: Water bath with aeration lines being assembled. Two baths are used. On the right side, the layout of the flasks can be found.

Samples were aerated by pushing air through the lines, as seen in Figure 13, for 70 min. using a laboratory bench air nozzle at 150 kPa. The oxygen concentration in the flask headspace was measured using a syringe to draw 30 mL at 10 min. intervals for 90 minutes. Vacuum containers were used to store the samples.

Samples were taken from the center and the top of the vessel, as shown in Figure 14. For the first sampling event, only one sample was taken from the compost vessels. Therefore, considering there were 12 vessels, respirometry was done on twelve compost samples and one blank flask, filled with ambient air, was used as a standard. Therefore 117 containers were filled in the first sampling event. The second sampling event was one week after the beginning of the experiment. The gas samples were then analyzed by gas chromatography. Headspace gas samples were injected into pre-evacuated 20 mL Exetainers (Labco, High Wycombe, UK) for storage until analysis for O_2 on a gas chromatograph. The greenhouse gas analyzer (GC 450, Bruker, Karlsruhe, Germany) was the machine used to do the analysis of the gasses CO_2, N_2O, CH_4 and O_2. The samples were injected simultaneously into an electron capture detector (ECD), thermal conductivity detector (TCD) and flame ionization detector (FID). Oxygen was analyzed on the FID and the carrier gas was helium.

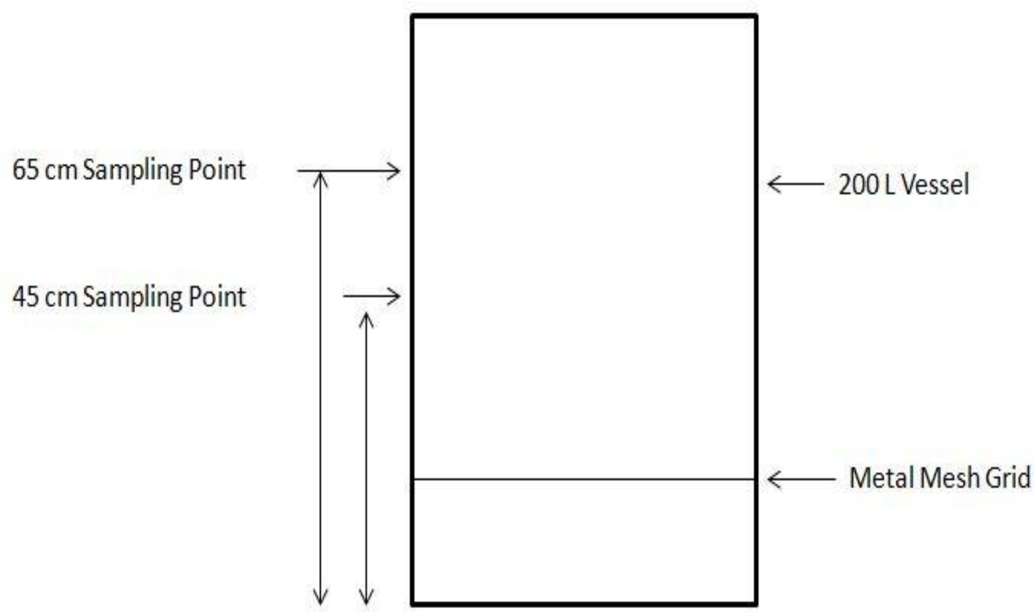

Figure 14: 200L Vessel with sampling points depicted on the left.

Total solids and moisture content

Total solids and moisture content were measured as per Thompson et al. (2002). The weights of thirty six foil oven dishes were measured and 50 mL of compost were placed into each dish. The samples were oven dried at 70°C for 24 hr. The samples were then cooled to ambient temperature, re-weighed and the difference in weight noted. The dry solids fraction represents the total solids and the evaporated fractions represent the percent moisture.

C/N Protocol

The carbon to nitrogen analysis involved drying a portion of each sample for all the treatments at 75°C for six hours. Afterwards, 60-70 mg of the sample were weighed and placed in a tin cup. These cups were then folded on themselves using tweezers and the precise weight was recorded. The samples were then placed in a ThermoFisher NC analyzer (FlashEA series 1112, ThermoFisher, Waltham, MA).

According to Bernal et al. (2009) there are three criteria that determine whether compost is mature: (i) the oxygen consumption rate of the compost must be less than 150 mg/kg of solids ventilated per hour; (ii) the carbon to nitrogen ratio must be under 25, and (iii) the composting vessels should either not be warmer than 20°C or not higher than the ambient temperature surrounding the compost. The paper also states that the lower the carbon to nitrogen ratio is, the greater the chance that the compost mixture is cured. Therefore, the analysis of the C/N ratio would be used as a complement to the oxygen and temperature analysis to determine whether the contents of the composting vessels are mature.

Compost samples were taken, as mentioned, at the beginning of the experiment and once every 14 days until 42 days into the compost run, for a total of four sampling events. Samples were taken at 65 and 45 cm from the bottom of each vessel. After total moisture, total solids and respirometry measurements were done, a portion of each sample was analyzed for carbon to nitrogen ratio. The evolution of the C/N ratio can be used as in indicator of the maturity of the compost. The PROC MEANS method of the SAS® statistical software (Littell, 2006) was used to determine whether there was a significant difference amongst the different treatments, and between the sample from the top and bottom of the vessels.

5. RESULTS

The HRS vessel 1 (Fig. 15) attains 55°C within 5 days and maintains these temperatures for 5 days. This would fulfill the CCME guidelines for grade A compost (CCME, 2005).

The second replicate attains 55 °C within 3 days, as depicted in the Figure 16 and maintains these temperatures for over 4 days. There was a spike in temperature at day 40. This cannot be explained. The third replicate attains 55°C within 7 days and maintains this temperature for 6 days (Fig. 17). Finally, the fourth replicate attains 55°C within 8 days and maintained higher or equivalent temperatures for 6 days (Fig. 18).

Temperature data and heat redistribution

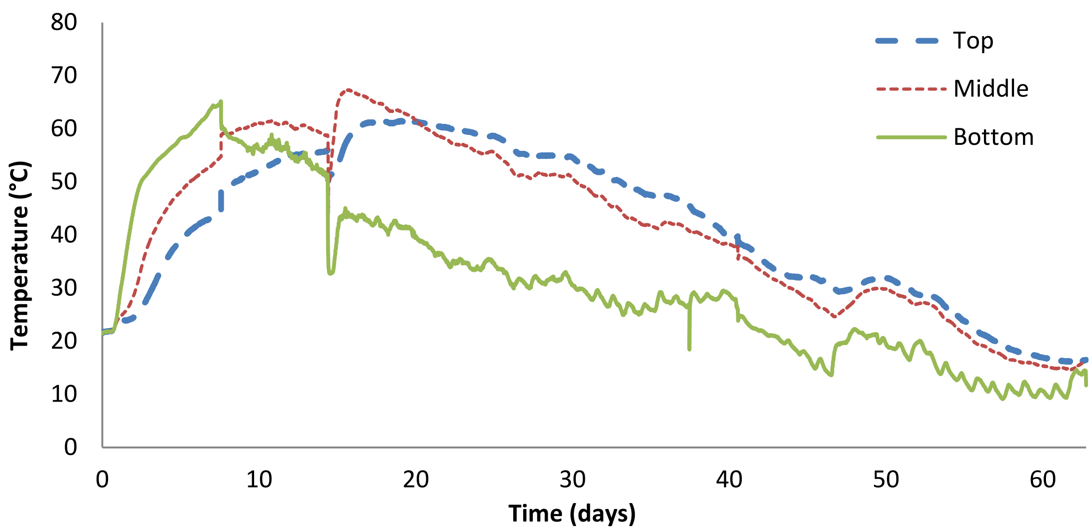

Figure 15: Heat Redistribution System 1: Temperatures for the top, middle and bottom thermocouples vs. time are plotted. Top element in legend represents probe at 74 cm, Middle represents the probe at 54 cm and Bottom represents 33 cm from the bottom of the vessel.

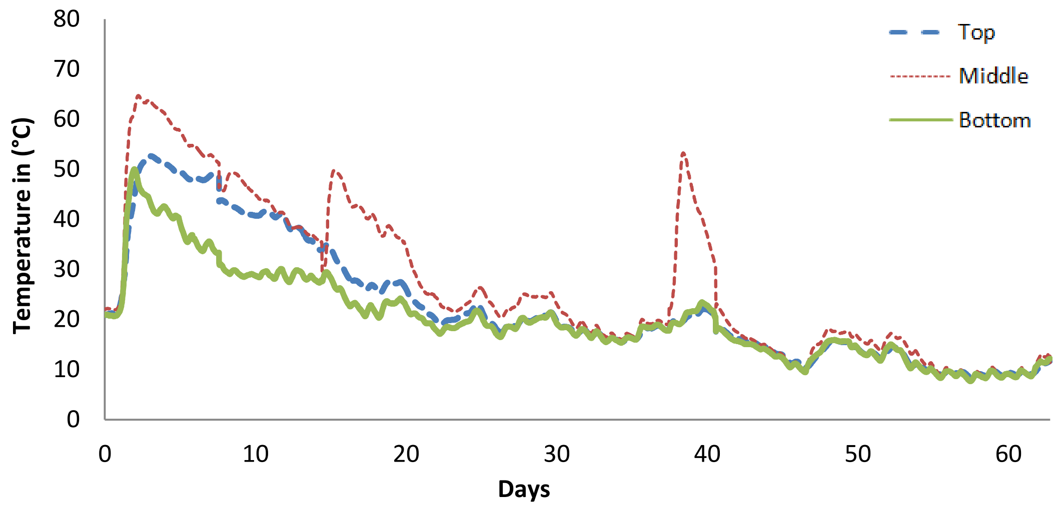

Figure 16: Heat Redistribution System 2: Temperatures for the top, middle and bottom thermocouples vs. time are plotted. Top element in legend represents probe at 74 cm, Middle represents the probe at 54 cm and Bottom represents 33 cm from the bottom of the vessel.

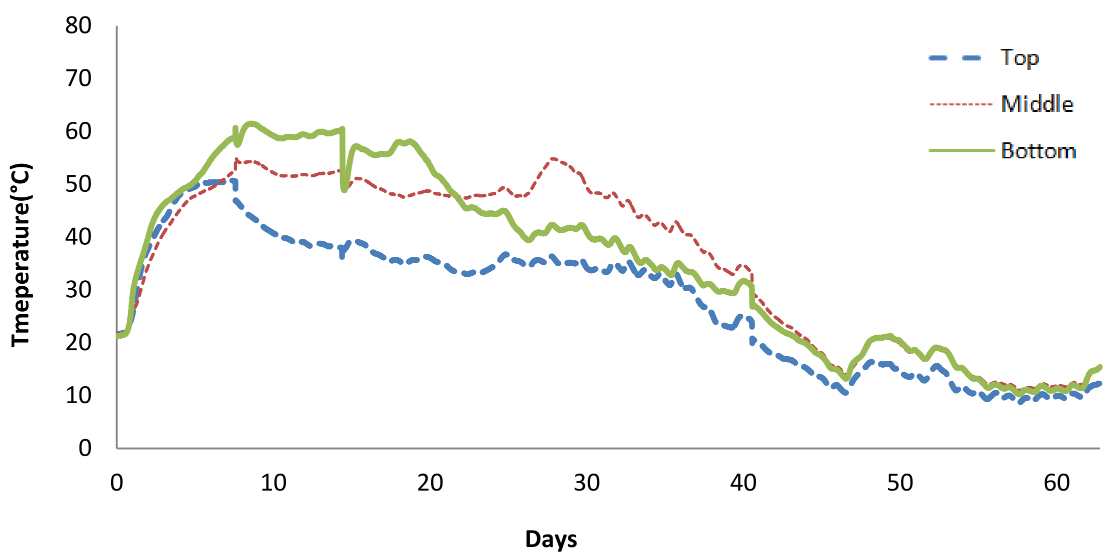

Figure 17 Heat Redistribution System 3: Temperatures for the top, middle and bottom thermocouples vs. time are plotted. Top element in legend represents probe at 74 cm, Middle represents the probe at 54 cm and Bottom represents 33 cm from the bottom of the vessel.

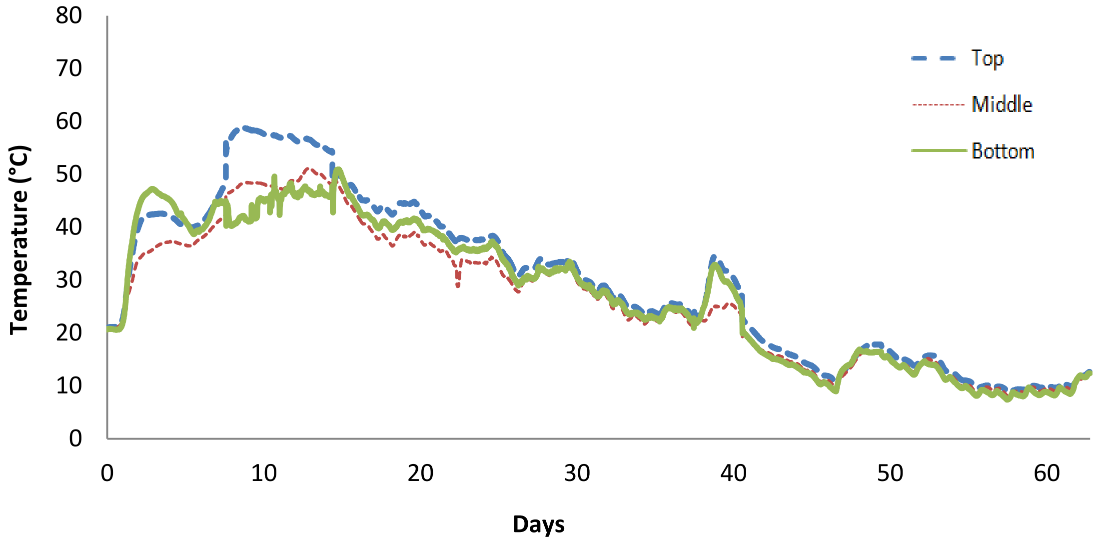

Figure 18: Heat Redistribution System 4: Temperatures for the top, middle and bottom thermocouples vs. time are plotted. Top element in legend represents probe at 74 cm, Middle represents the probe at 54 cm and Bottom represents 33 cm from the bottom of the vessel.

Control vessel results

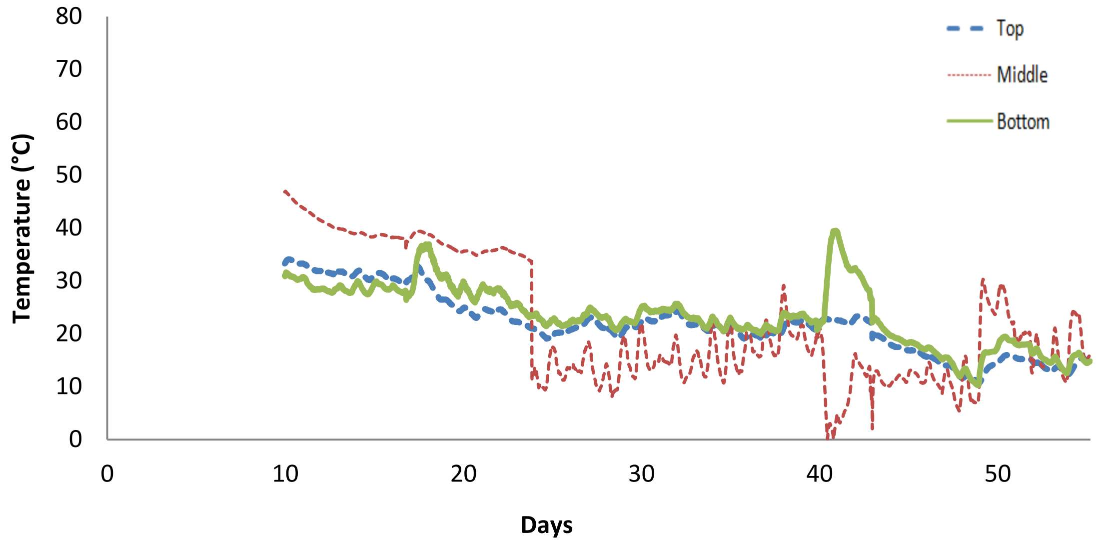

Figure 19: Control 1: Temperatures for the top, middle and bottom thermocouples vs. time are plotted. Top element in legend represents probe at 74 cm, Middle represents the probe at 54 cm and Bottom represents 33 cm from the bottom of the vessel.

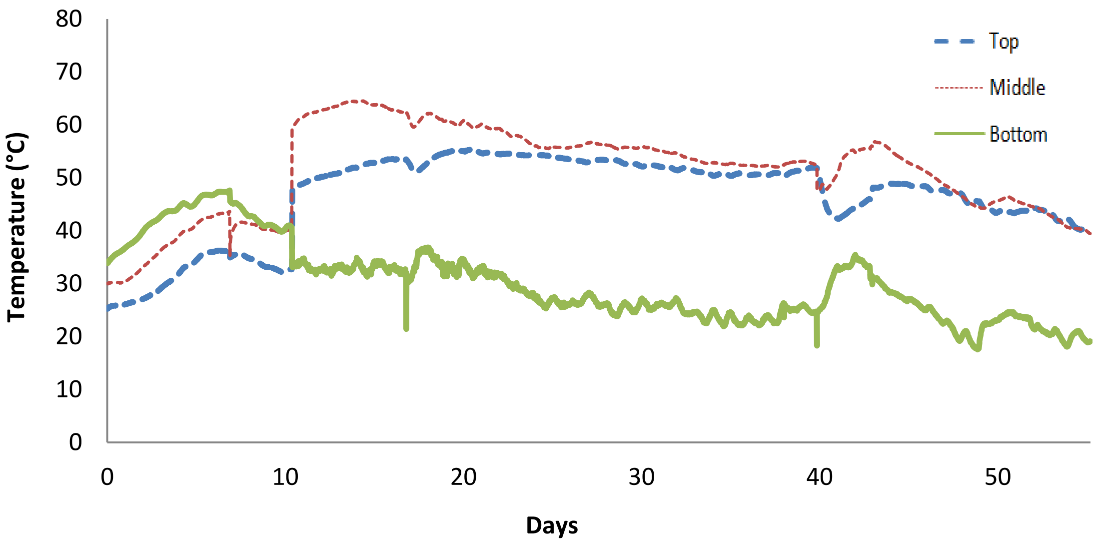

Figure 20: Control 2: Temperatures for the top, middle and bottom thermocouples vs. time are plotted. Top element in legend represents probe at 74 cm, Middle represents the probe at 54 cm and Bottom represents 33 cm from the bottom of the vessel.

The control vessel 1, depicted in Figure 19, has the first 10 days of data missing due to data logger issues, therefore, the maximum temperatures attained could not be determined. Thermocouple seems to be poorly connected after day 23.

The control vessel 2 (Fig. 20) had the first 10 days of data missing due to data logger issues, therefore, the maximum temperatures attained could not be determined. Although one can notice, from visual inspection that temperature gradients are fairly larger for vessel 2 than the HRS treatment by inspecting Fig. 19. Bottom thermocouple seems to have disconnected after day 10.

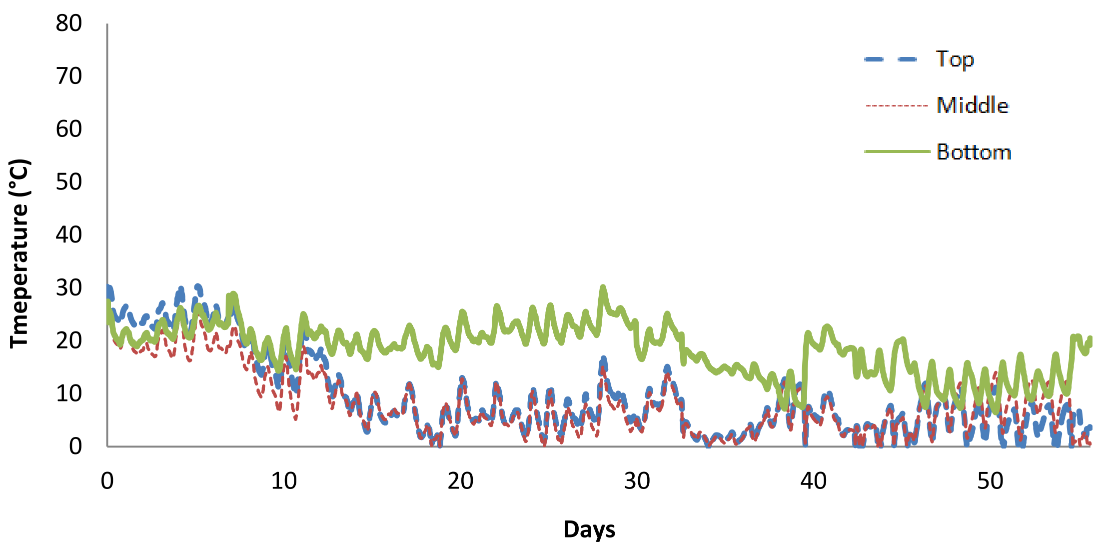

Figure 21: Control 3: Temperatures for the top, middle and bottom thermocouples vs. time are plotted. Top element in legend represents probe at 74 cm, Middle represents the probe at 54 cm and Bottom represents 33 cm from the bottom of the vessel.

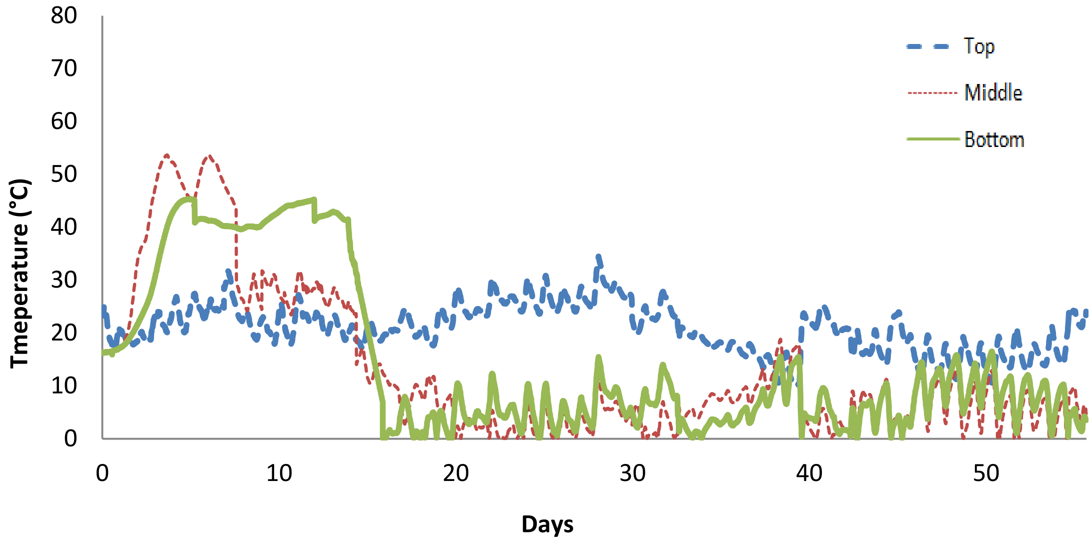

Figure 22: Control 4: Temperatures for the top, middle and bottom thermocouples vs. time are plotted. Top element in legend represents probe at 74 cm, Middle represents the probe at 54 cm and Bottom represents 33 cm from the bottom of the vessel.

Control vessel 3, shown in Figure 21, did not attain 55°C, nor did it attain the thermophilic phase, although C/N ratio and moisture levels, discussed later, were within the recommended range. The thermocouples do not give reliable data. Something went wrong with data collection in this vessel. Although the control vessel 4 in Figure 22 attains 55°C, it does not maintain this temperature for 3 consecutive days. None of this data seems reliable due to major dips in temperature readings.

Air exchange system results

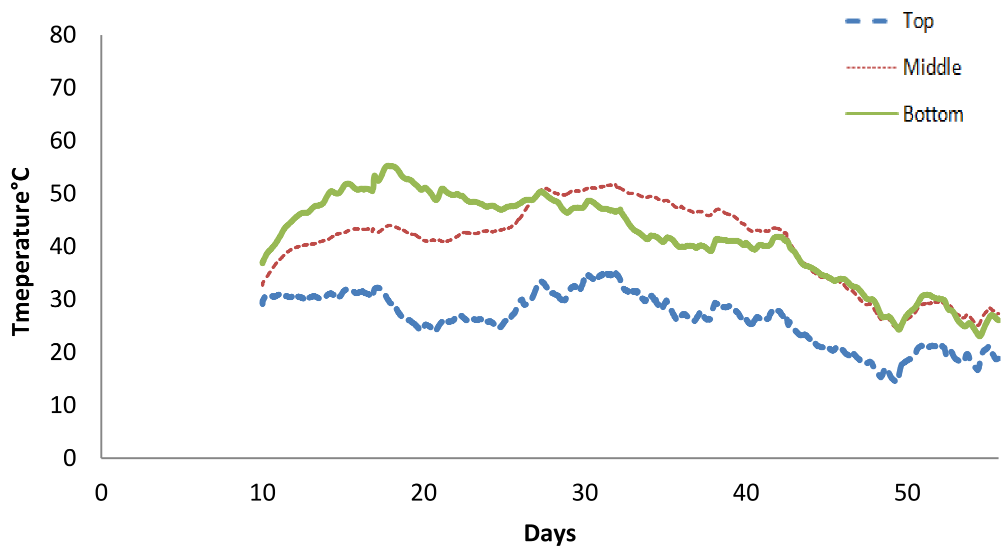

Figure 23: Air heat exchanger 1: Temperatures for the top, middle and bottom thermocouples vs. time are plotted. Top element in legend represents probe at 74 cm, Middle represents the probe at 54 cm and Bottom represents 33 cm from the bottom of the vessel.

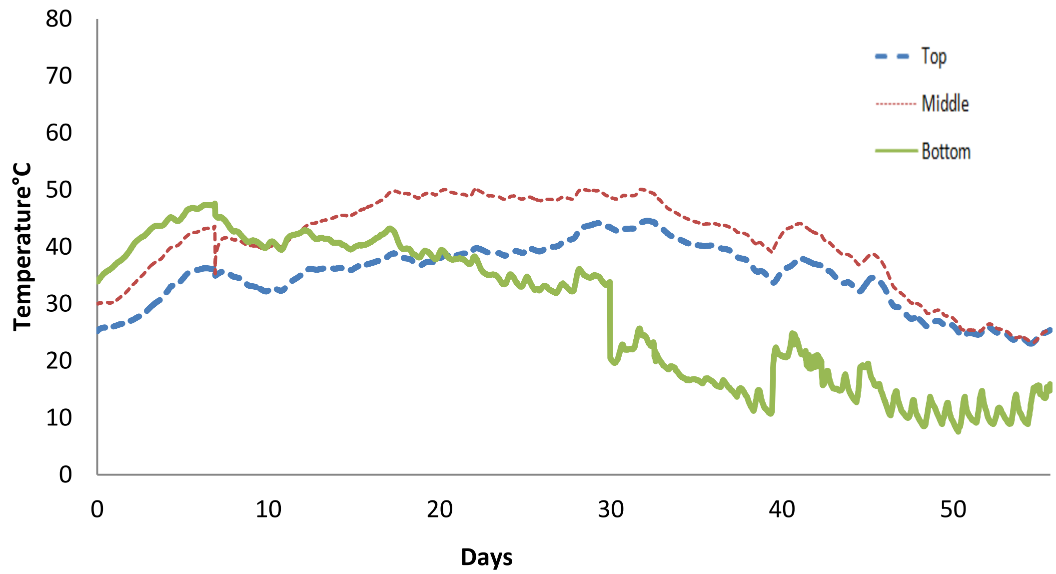

Figure 24: Air heat exchanger 2: Temperatures for the top, middle and bottom thermocouples vs. time are plotted. Top element in legend represents probe at 74 cm, Middle represents the probe at 54 cm and Bottom represents 33 cm from the bottom of the vessel.

It should be mentioned that due to data logger issues, essentially a data board failure, days 0 to 10 were not recorded for the AES vessel 1 (Fig. 23). The AES 1 attains 55°C and maintains it for over 5 days. The vessel for AES 2 does not attain 55°C (Fig. 24). The bottom thermocouple does not seem to give reliable data after day 8.

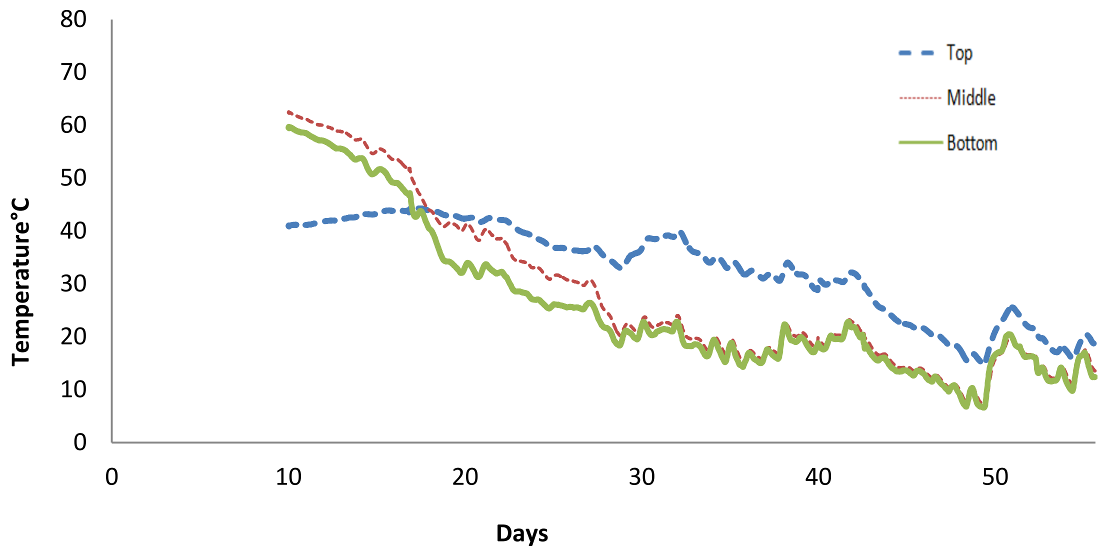

Figure 25: Air heat exchanger 3: Temperatures for the top, middle and bottom thermocouples vs. time are plotted. Top element in legend represents probe at 74 cm, Middle represents the probe at 54 cm and Bottom represents 33 cm from the bottom of the vessel.

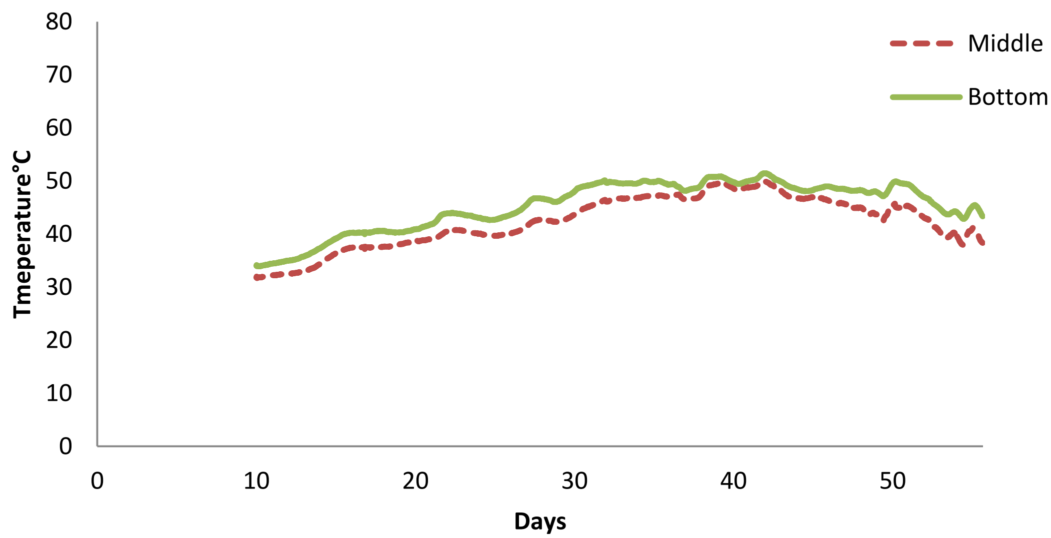

Figure 26: Air heat exchanger 4: Temperatures for the top, middle and bottom thermocouples vs. time are plotted. Top element in legend represents probe at 74 cm, Middle represents the probe at 54 cm and Bottom represents 33 cm from the bottom of the vessel.

AES 3 data for day 0 to 10 was not available due to data logger issues. AES replicate 4 data for day 0 to 10 was not available due to data logger issues. The top thermocouple readings were deleted, due to unreliable data collection.

Carbon to Nitrogen Ratios Data

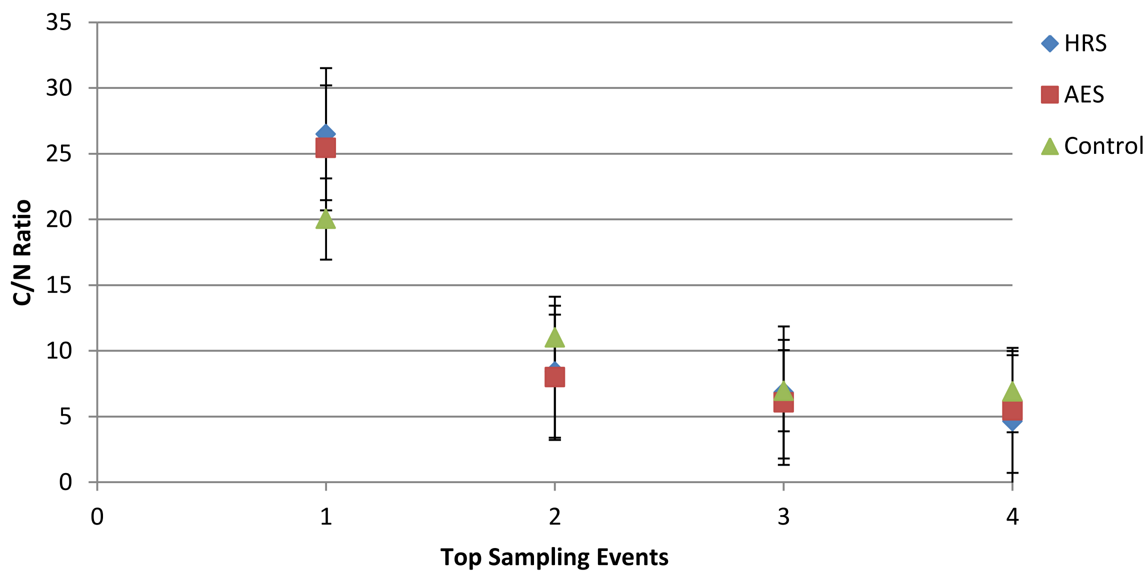

Figure 27: Carbon to nitrogen ratios for sampling events at the top of each vessel where 1, 2, 3 and 4 refer to time frames of day 1, day 14, day 28 and day 42 respectively. Population of n=4.

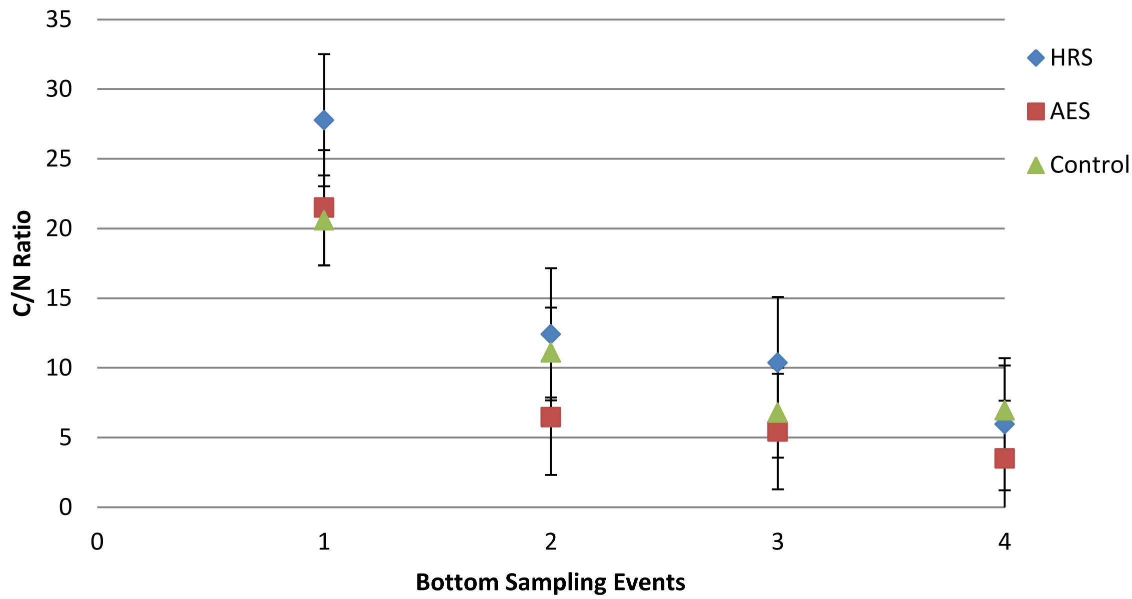

Figure 28: Carbon to nitrogen ratios for sampling events at the top of each vessel where 1, 2, 3 and 4 refer to time frames of day 1, day 14, day 28 and day 42 respectively. Population of n=4.

All initial C/N ratios were between 20 and 35. This would indicate that initial mixtures were adequate for composting to occur.

Temperature Analysis

To manage the large number of data points, SAS PROC MEANS was used to determine the means for every 24 h of data tabulated from the data loggers. Note that the 4 HRS vessels data extends until 65 days unlike the other two treatments that end at 55 days. This is due to a datalogger issue.

The TYPE option was used in the REPEATED statement of SAS PROC MIXED to specify a covariance structure based on depth of the probe in the composting vessels. In this case, the Type III Tests of Fixed Effects indicated that the treatment effect, control vs AES vs HRS was significant ($p < .0001$). The differences between the treatments least-squares means was assessed using the LSMEANS statement (Chandler, 1995), and the differences between all the treatments were significant (Fig. 29): AES > CONTROL ($p < 0.0001$), AES > HRS ($p = 0.0081$), HRS > CONTROL ($p < 0.0001$).A similar model was analyzed using a covariance structure based on time, and the treatment effect was only significant at the $\alpha = 0.1$ level ($p = 0.0685$). The AES treatment temperatures were higher than the HRS and control (unadjusted $p = 0.0420$ and 0.0446, respectively).

SAS PROC PLOT was used with the locally weighted scatterplot smoothing option. To produce Figure 29, SMOOTH = 1, and $\alpha = 0.1$ were specified for the confidence limits.

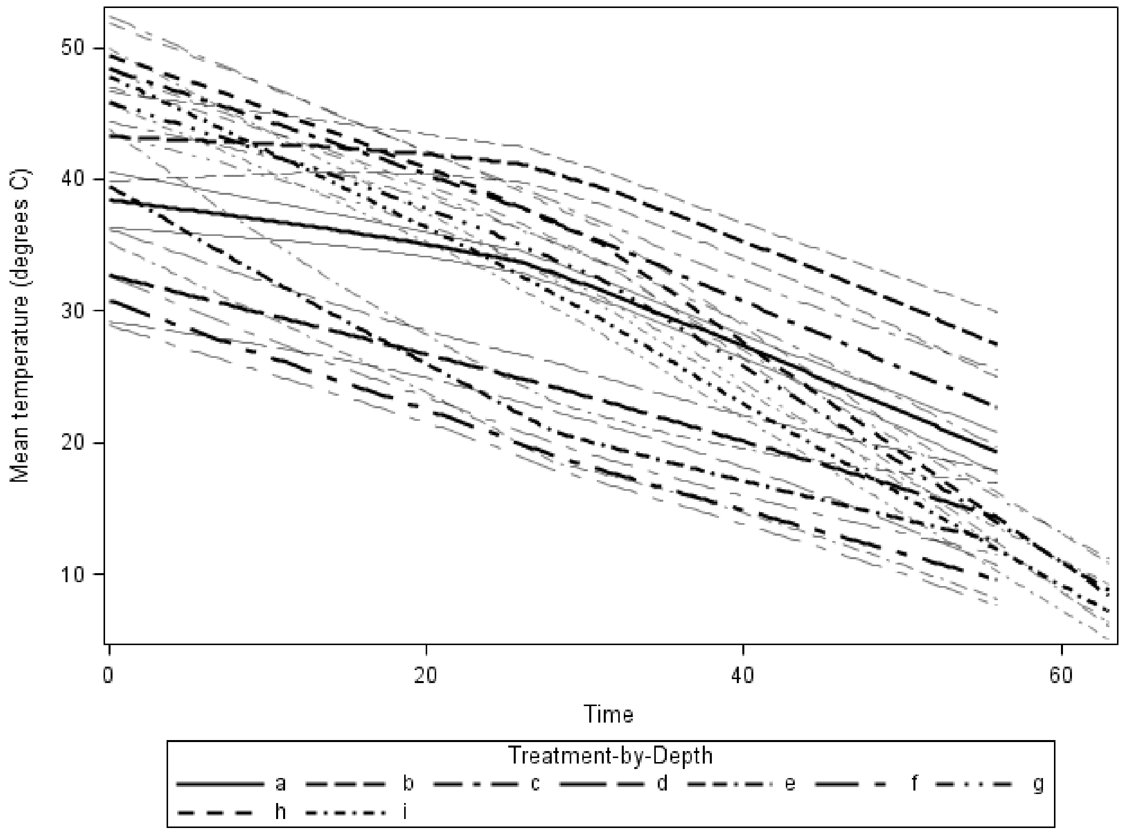

Figure 29: AES depth 1 = a; AES depth 2 = b; AES depth 3 = c; control depth 1 = d; control depth 2 = e; control depth 3 = f; HRS depth 1= g; HRS depth 2 = h; HRS depth 3 = i. Time is measured in days and temperature in degrees Celsius.

To produce Figure 30 the same data was used, but specifying SMOOTH= 0.1

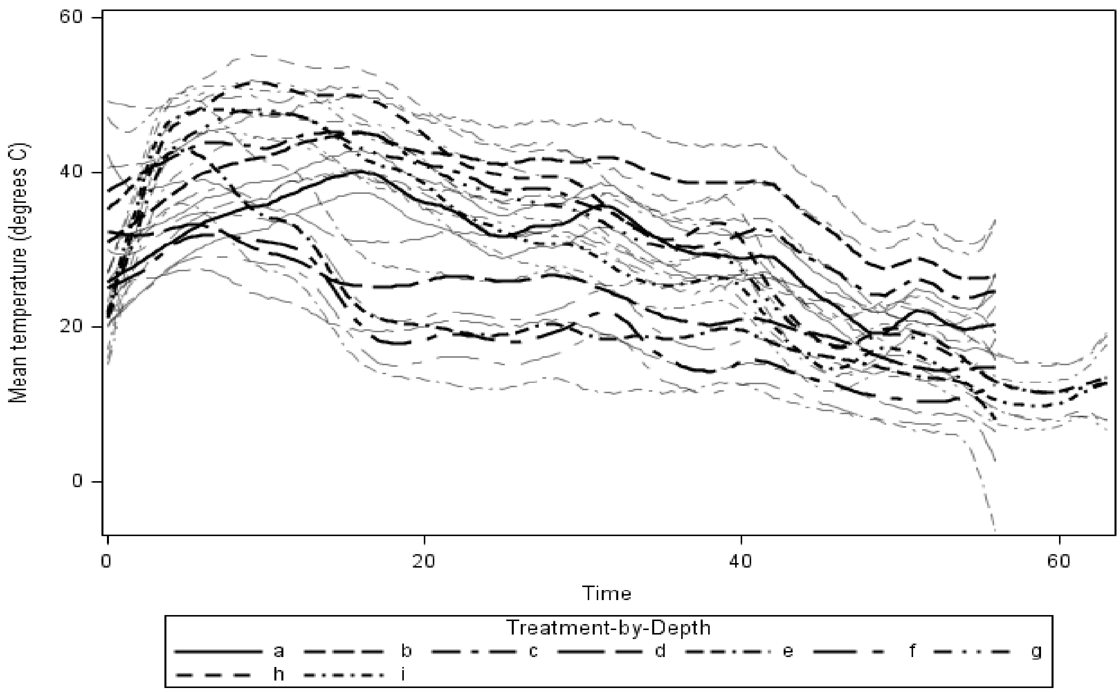

Figure 30: AES depth 1 = a; AES depth 2 = b; AES depth 3 = c; control depth 1 = d; control depth 2 = e; control depth 3 = f; HRS depth 1= g; HRS depth 2 = h; HRS depth 3 = i, SMOOTH= 0.1. Time is measured in days and temperature in degrees Celsius.

Since the difference between the treatments over time was insignificant (owing to the multiple comparisons being made) the lack of significant differences between depth level temperatures over time was not surprising. SAS PROC MEANS for 24 hour intervals and PROC MIXED and a spatial covariance structure based on time. The Type III Tests of Fixed Effects produced p-values that indicated the insignificance of the treatment effect on the difference between the top and middle temperatures ($p = 0.31$); the top and bottom temperatures ($p = 0.38$); the middle and bottom temperatures ($p = 0.84$). See Figure 31.

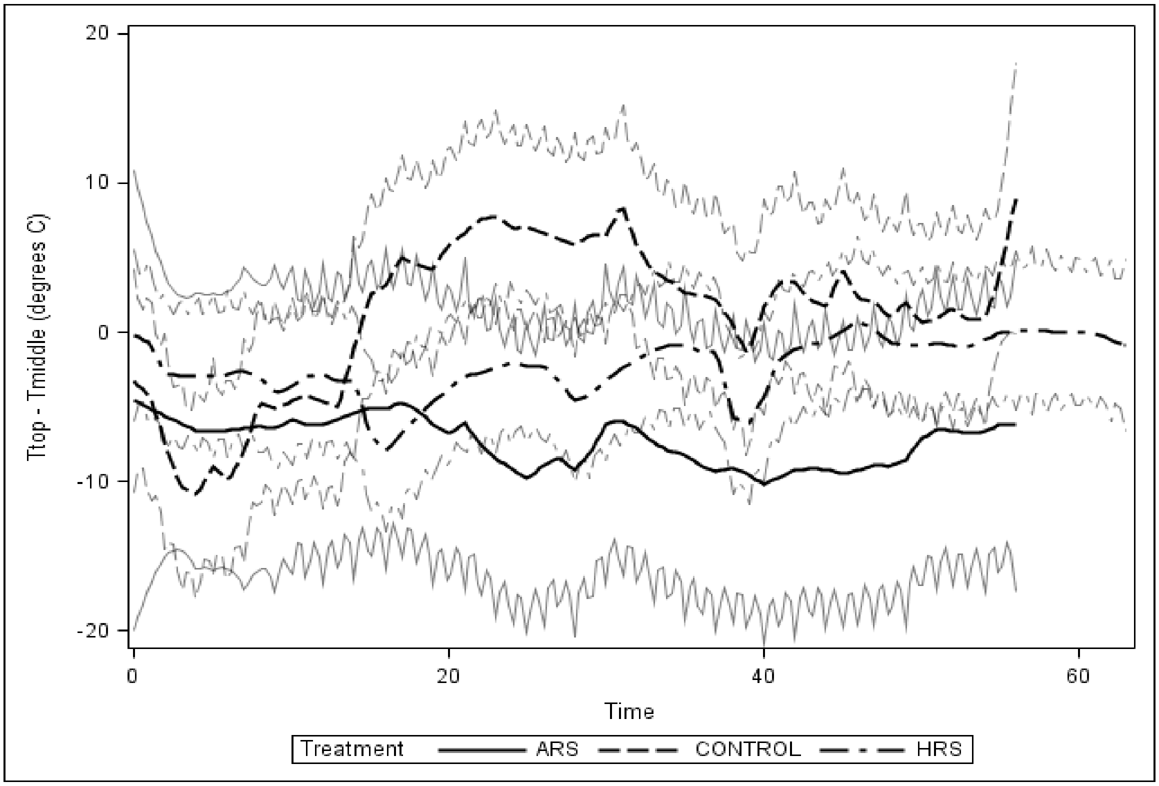

Figure 31: AES depth 1 = a; AES depth 2 = b; AES depth 3 = c; control depth 1 = d; control depth 2 = e; control depth 3 = f; HRS depth 1= g; HRS depth 2 = h; HRS depth 3 = i.

Also, in Figure 32, one can see the difference between the temperatures of the middle and bottom depths is higher for the control and AES but only briefly, early in the experiment.

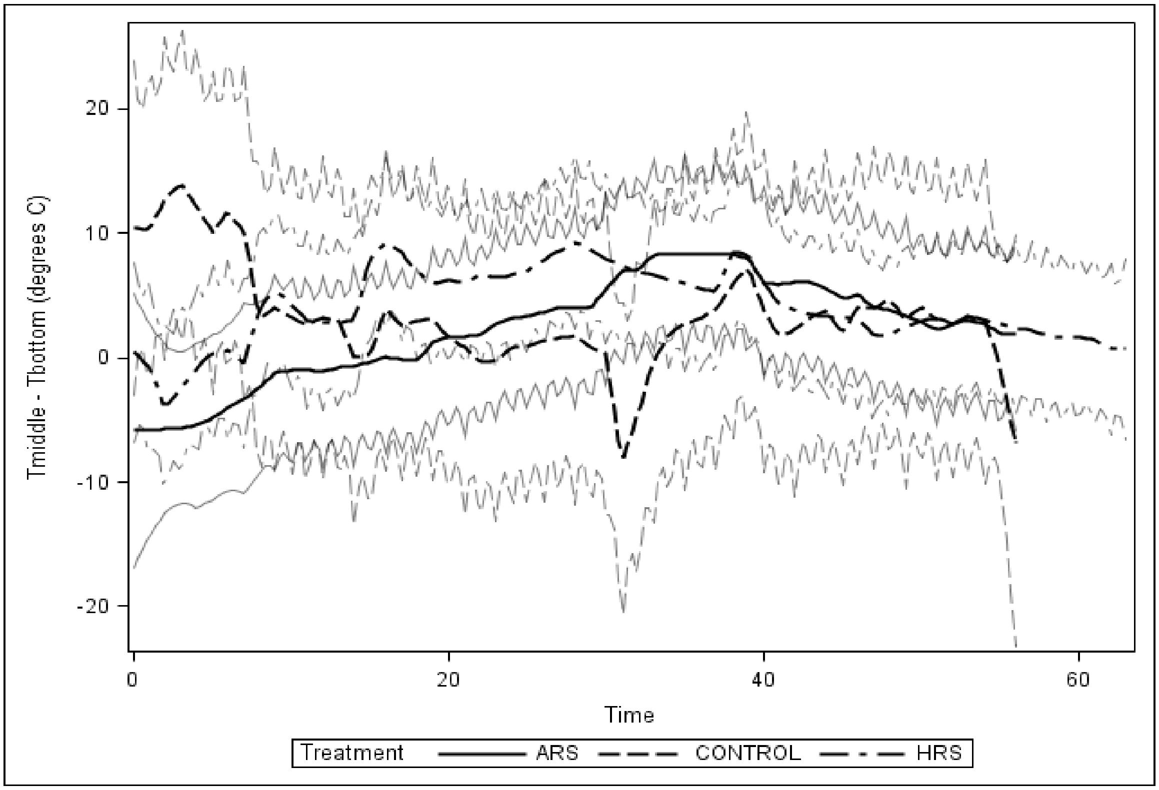

Figure 32: AES depth 1 = a; AES depth 2 = b; AES depth 3 = c; control depth 1 = d; control depth 2 = e; control depth 3 = f; HRS depth 1= g; HRS depth 2 = h; HRS depth 3 = i

Carbon to Nitrogen Statistical Analysis

The data was assessed using PROC MIXED in SAS, with a covariance structure based on time. However, the Type III Test of Fixed Effects for the model did not reveal any significant factors. Therefore, it was established that the C:N ratio data conformed to the conventional statistical assumptions. The Shapiro-Wilk statistic (Leslie *et al.*, 1986) was used and confirmed the Normal distribution for the data from each day of measurement. The homogeneity of the variance was established by a chi-squared test for the data from each day of measurement.

The data was sorted by day, and using PROC MIXED the significance of the factors and their interaction was assessed. With respect to day 1, the Type III Test of Fixed Effects indicated that the treatment effect ($p = 0.085$) and interaction (location × treatment) effect ($p = 0.075$) were significant at only low levels. Note location refers to bottom and top sampling points.

On days 14 and 28, the interaction effect was significant, the Type III Test of Fixed Effects indicated p = 0.0047 and 0.0374, respectively. On day 14, there was a significant difference between the C:N ratios at the bottom and at the top of the AES system ($mean_{top}$ = 7.9851, standard error = 1.2488; $mean_{bottom}$ = 12.4065, standard error = 1.2488; significance of the difference after Scheffé's adjustment = 0.0397). On day 28, Scheffé's adjustment discounted any apparent differences between the interaction levels. On day 42, the Type III Test of Fixed Effects indicated the significance of the treatment effect (p = 0.0415). The C:N ratios for the HRS system were lower than the controls ($mean_{HRS}$ = 4.0761, standard error = 0.7317; $mean_{control}$ = 6.9260, standard error = 0.7317; Bonferroni-adjusted p = 0.0392).

6. DISCUSSION

Temperature Data Conclusions

The statistical analysis leads to the conclusion that the temperature differences within the vessels are only significant, briefly at the beginning of the experiment, essentially between day one and day 10 ($p < 0.0001$). During this period of time, temperature within the vessels fitted with the HRS systems averaged 41.9°C were as the control vessels averaged 34.2°C. This suggests that the overall temperature within the controls is 7.7 °C lower than the HRS fitted vessels. Taking into consideration that the statistical data suggests that temperature gradients are also lower within the vessels fitted with the HRS and that previous calculations suggest that heat redistribution within the HRS system should start occurring around 25° C, one could conclude that the system is contributing to higher overall temperatures within that period of time and lower temperature differences. The role of the HRS was to redistribute evenly the core heat within the composting vessel throughout the compost media. The above statement leads one to conclude that the system is accomplishing its intended purpose. An important element to touch upon would be the sudden change in temperature readings at day 10. This could have been due to thermocouples failing due to corrosion or mishandling. Students were asked to help clean the compost area and might have hooked the data loggers or the thermocouple cables displacing the thermocouples and affecting the connection to the terminals.

The initial stages of the composting process are aided by the redistribution of heat throughout the compost bed, permitting the composting vessel to attain thermophilic temperature levels earlier than the control vessels. It is important to note that due to data logger handling issues, the first 8 days of temperature readings from the AES fitted vessels were not recorded for AES 1, 3 and 4. AES 2 however does provide reading for the first ten days, yielding an average temperature of 37.2°C. Although this value only represented one vessel, it was still over 3°C higher than the control vessels. One should also note that the objective of the air exchange system was to reduce heat loss from the top aeration hole of the vessels.

Another conclusion brought about by the statistical analysis of temperature data suggests that the controls experience higher temperature differences after forty days up to the end of the experimental period compared to the HRS fitted vessels. This could be due to the higher overall temperatures of the HRS fitted and AES fitted vessels up to 40 days of experimentation. For example, the average temperature for the HRS fitted vessels was 40.9°C; 38.0°C for the AES fitted vessels and 26.3°C for the controls. However, for the rest of the experimentation period, the HRS vessels exhibit lower temperatures. From 40 to 60 days, the HRS fitted vessels averaged 18.7°C were as the controls exhibited 20.1°C. One could hypothesize that the HRS fitted vessels get to maturity quicker than the control vessels.

Although the statistical analysis does not necessarily demonstrate an overall significance in the temperature difference between the HRS, AES and control vessels throughout the entirety of the experiment, as mentioned above, if specific segments of the data are analyzed, such as the mesophilic phase, or warming phase and the thermophilic phase, by visual inspection of the graphs, one notices that the HRS vessels, as mentioned previously attain higher temperatures and exhibit a more pronounced warming curve, although this is not statistically proven. It was assumed that the heat redistribution system would start functioning close to 25°C. Convection and conduction, through the copper tubing, from the center of the vessel to its extremities is assumed to cause heat flow throughout the HRS system. This mechanism would promote the compost mixture to maintain the same composting phase throughout the composting process.

Carbon to Nitrogren Data Conclusions

There seems to be a significant difference between C/N values at the beginning of experimentation, $p = 0.085$ and location versus treatment $p = 0.075$. This would suggest that the mixture was not homogeneous at day 1, possibly mixing was not properly done. However, the initial C/N values are all within the ideal composting range 20-35 (Hermann, 1997).

The C/N data not being conclusive, one must turn towards the temperature data to determine the maturity of the compost. C/N reading past the first C/N sampling event does not show a particular pattern. All vessels however do exhibit lower C/N ratios throughout the experimentation suggestion carbon consumption is going on. The statistical analysis suggested that at 42 days, the HRS vessels exhibit lower C/N ratios than the controls and AES vessels. The Type III Test of Fixed Effects indicated the significance of the treatment effect ($p = 0.0415$). The C:N ratios for the HRS system were lower than the controls and AES vessels. This, along with the temperature data obtained from the HRS vessels, would permit one to suggest that the HRS treatment attains maturity quicker than the other treatments due to higher temperatures.

Considering there was a significant difference between carbon to nitrogen ratios at the beginning of experimentation ($p=0.085$), one could conclude that the compost mixture was not homogeneous. Location versus treatment C/N ratios yielded a p value of 0.075 on day 1, meaning the initial samples demonstrate different mixtures at the top and bottom sampling points. The mixing technique could have been inadequate. This is a significant finding as it could invalidate the claim that the compost mixture was homogeneous at the beginning of the experiment.

Respirometry Data

One would expect oxygen levels to go down during the experiment. This would demonstrate, as explained previously, that micro-organisms are using less oxygen, therefore the compost is closer to being cured or mature. Figure 41 represents the flask design used to store and aerate the sample of compost until air extraction.

Air could have leaked into the Erlenmeyer flasks through the stopper assembly, or between the stopper assembly and the flask. This would explain the data graphs found in Appendix B to have the majority of the data indicate 20% oxygen levels, which is equivalent to ambient air oxygen levels. Therefore, the oxygen data was not considered when evaluating the maturity of the compost samples. Also note that the vacuumed containers were not tested for oxygen content until 5 months past extraction date. This was due to the laboratory assistants being overwhelmed with other projects. In any future endeavor an oxygen probe, along with a tighter rubber stopper or more appropriate flask assembly could be used to evaluate oxygen consumption and run respirometry testing. This would also eliminate the need for sending samples to an independent laboratory for gas chromatography testing.

Conclusion

To summarize, the objective of testing the effectiveness of the heat redistribution system (HRS) (Fig. 1) to transfer heat throughout the compost media and permit uniform composting, resulting in cured final product and of testing an AES that would reduce heat loss from the top aeration holes was not accomplished. However, one can conclude that at the beginning of experimentation, the temperature levels in the HRS vessels were higher and the C/N data suggests that the HRS treatment permitted the compost to cure faster than the controls and AES vessels.

Twelve vessels were run using dog food and wood chips as a homogenized mixture. All vessels were instrumented with temperature measuring equipment and samples were taken throughout the 60 day experimentation period. These samples were taken to provide insight on the maturity of the compost within each vessel. The samples were tested for C/N ratio, respirometry, total solid content and moisture content. The sampling process took place at the beginning of the experimentation period and every 14 days until day 42.

Recommendations

The respirometry protocol was flawed possibly due to leakage from the top of the flasks used throughout the process. Rubber stoppers were used as lids and as mentioned in the discussion section, it is assumed that these stoppers caused ambient air to flow into the flasks skewing the data obtained from gas chromatography analysis. The aforementioned data seemed to display 20% oxygen level within the flasks, equivalent to ambient oxygen levels.

The C/N data suggested, statistically, that the vessels exhibit a significant difference between the top and bottom samples taken from the vessels at day 1. This led us to conclude that the vessels were not homogeneous at the beginning of experimentation. The statistical analysis, using SAS also concluded that the HRS vessels had significantly lower C/N levels than both of the other treatments $p = 0.0415$. Also, all HRS vessels attained and maintained 55°C for one or more thermocouples. As mentioned above, the C/N data suggested that mixing of the compost was not properly done at the beginning of the experiment as there was a significant difference between C/N values ($p=0.085$). Better mixing techniques should be envisioned for any future undertakings.

Temperature data statistical analysis suggested ($p<0.001$) that the HRS vessels, between day 1 and 10 exhibited higher temperature levels and between day 40 and 60 exhibit smaller temperature difference between thermocouples than the control vessels.

As mentioned previously, the experimental protocol design for respirometry was flawed. This is a part of the experimentation that should be revised for any future testing. As suggested in the discussion section, a better sealing process for the flasks and on hand oxygen measuring equipment should be implemented to avoid seepage and the loss of data. Another suggestion would be to run more replicates of the treatments. This would lead to a better understanding of the function of the AES and HRS systems. Temperature data analysis, along with regular sampling could also be done. Note that more sampling events would also have helped keep track of the progression of the composting process, this was not done due to budget and staff limitations. Data loggers should have been checked daily and data downloaded to avoid data losses.

The data obtained were not adequate to determine the effectiveness of the HRS or AES design from a statistical perspective. A more rigorous protocol should be built, possibly an experimental design running 20 vessels, five with the HRS, five with the AES, five fitted with both the AES and HRS and five controls. The composting process should be monitored with more sampling points and more sampling events. The area where the composting experiments are run should be heated and ambient moisture levels should be taken. Restricted access should be given to the area. However, one must note that the HRS did exhibit higher temperatures and smaller temperature differences at the beginning of experimentation, ranging up to 10 days. This would possibly indicate that the system was effective in promoting homogeneous composting at the beginning of the experiment and higher overall temperatures. Further testing is required to confirm this statement.

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Appendix A

THERMOCOUPLE CALIBRATION CURVES

DATA LOGGER 1

All thermocouples were calibrated before use with a resulting R^2 value above 0.999 for the first data logger set and above 0.99 for the thermocouples attached to the second data logger. Below are two samples of the calibration curves obtained for each data logger.

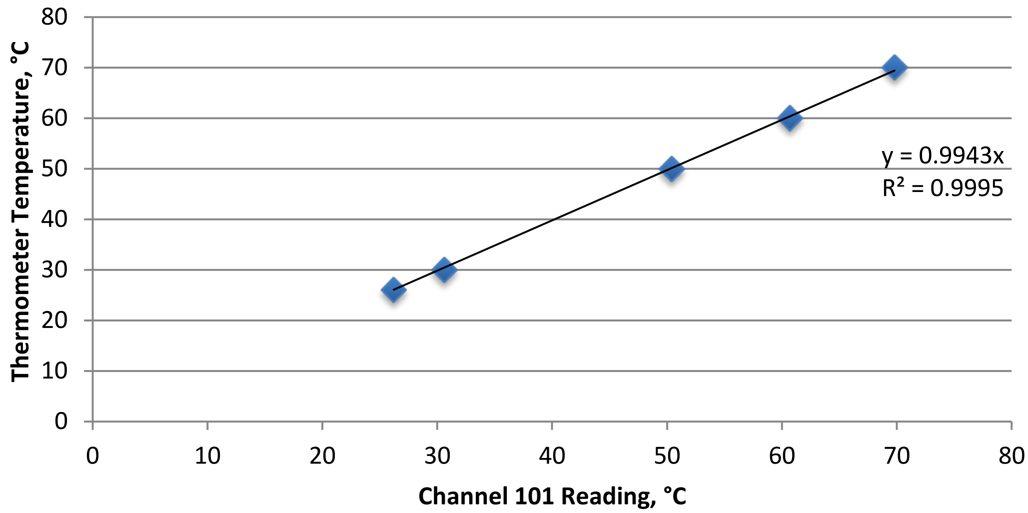

Figure 33: Calibration graphic of thermocouple 101, data logger 1.

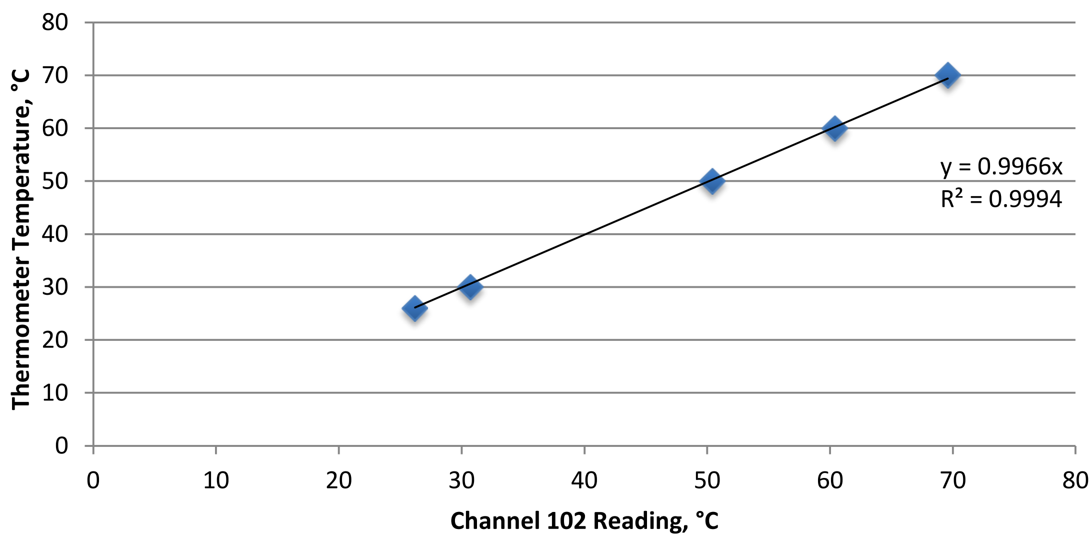

Figure 34: Calibration graphic of thermocouple 102, data logger 1.

DATA LOGGER 2

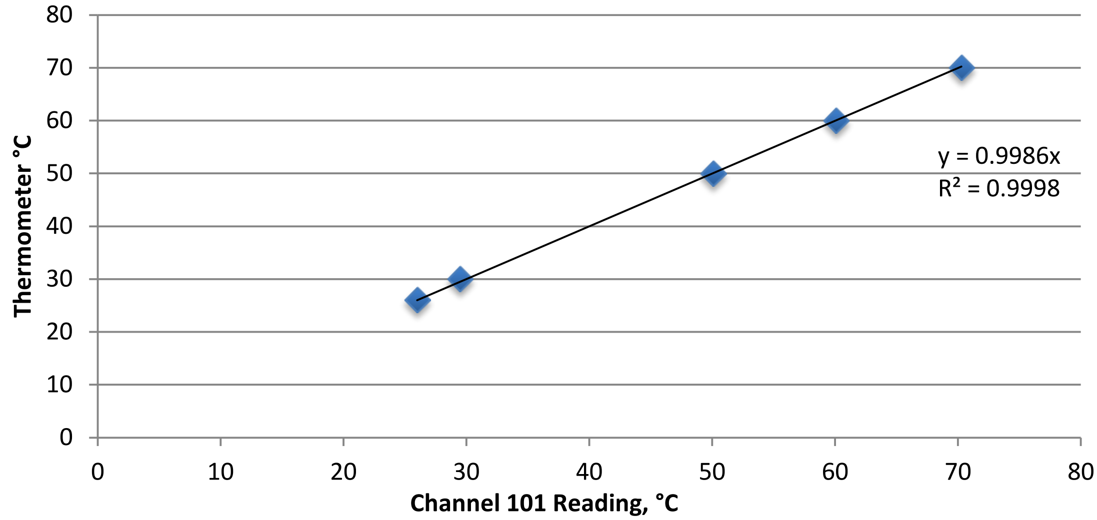

Figure 35: Calibration graphic of thermocouple 101, data logger 2.

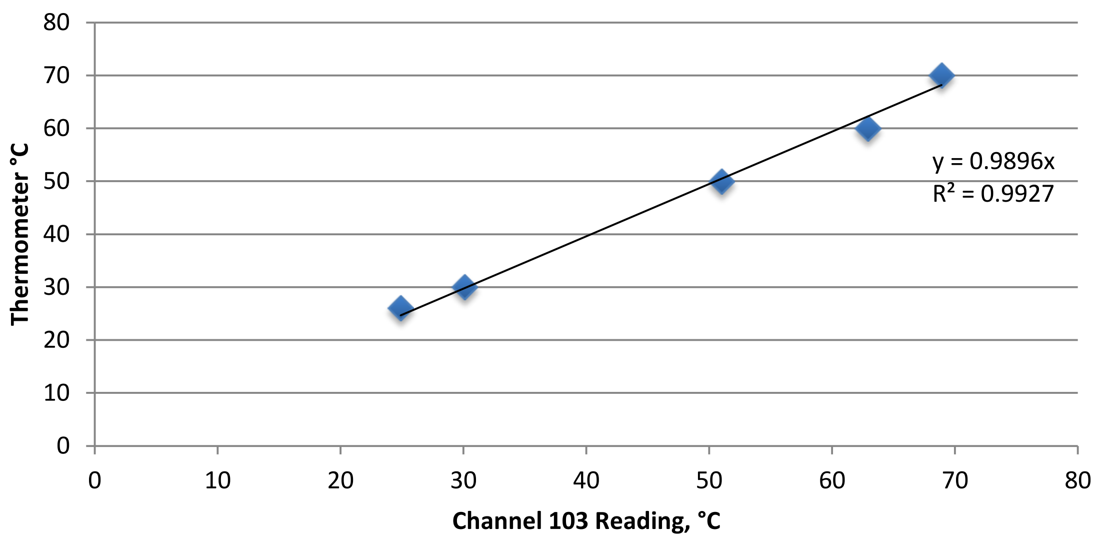

Figure 36: Calibration graphic for thermocouple 103, data logger 2.

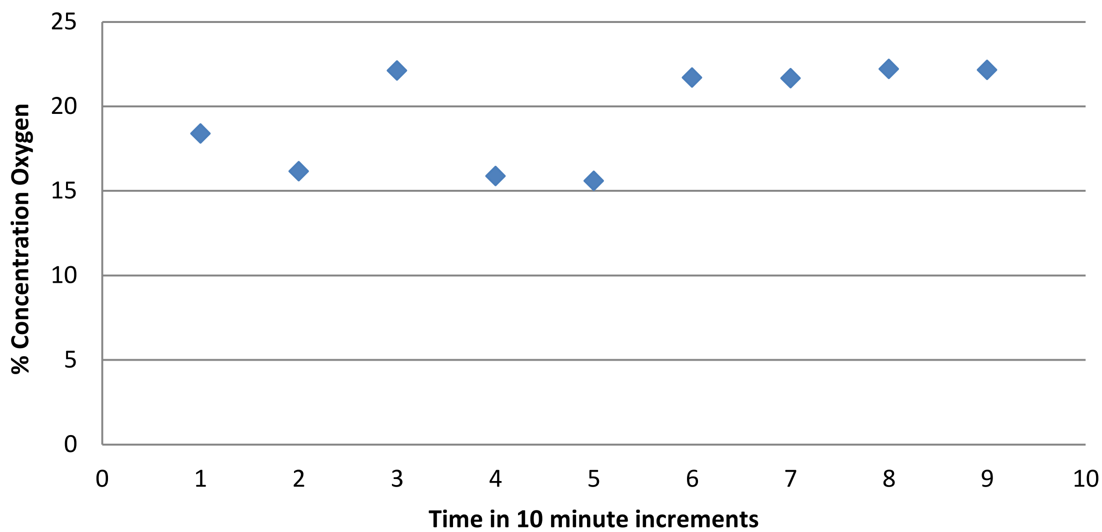

Figure 37: Blanks, air filled flask, Time vs % Concentration of Oxygen.

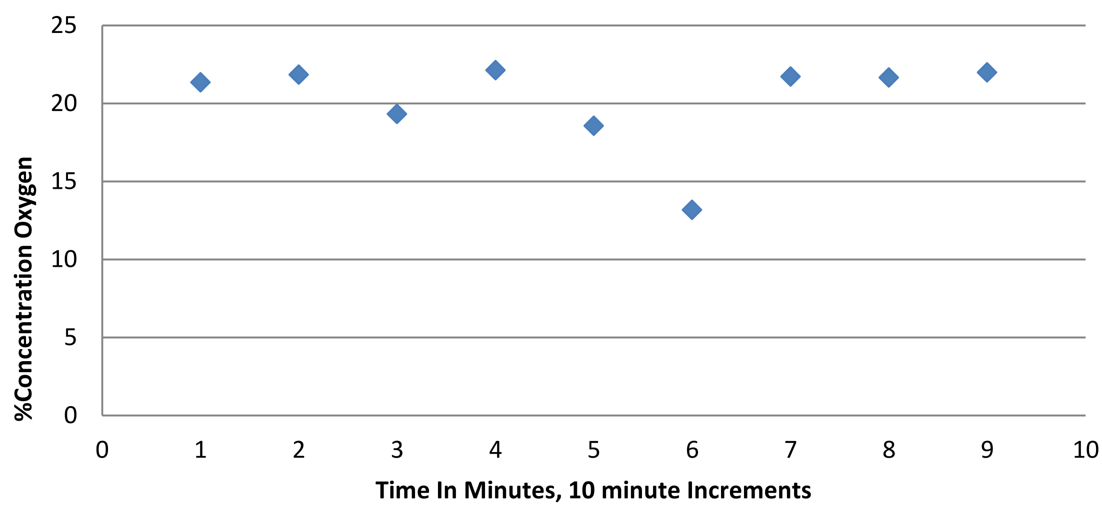

Figure 38: Top Sample Heat Redistribution System 1. Time vs % Concentration of Oxygen.

Appendix B

SAMPLE CALCULATION

Calculation of sizing & length of AES.

Known:
Thi= 55 °C
Tco= 30 °C
Tho= 15 °C
Tci= 14 °C
m= 5.6mg/kgs
Ktm= 65 w/mk
Amount of material in vessel= 92.5 kg of compost

5.6 mg/kgs * 92.5kg of organic matter = 0.518 kg/s of flow

q= mCpΔT

q= m (1.0065 kJ/KgK)(Thi-Tho)

q= (0.518kg/s)(1.0065KJ/kgK)(55-15)K

q= 20.85 W

1/((0.73 w/m^{2}k)* (2 πRoLs) + 1/((65W/mK)*(2 πRoLs) + 1/(0.70 w/m^{2}k)*)*(2 πRiLs)+

Ls/((65 w/mk)*(2 πRiLs)+ 1/((0.71 w/m^{2}k)*(2 πRiLs) = Rtotal K/W

Rtotal = 1.97 W = ((55°C-14°C)K)/20.85

Ro= 0.1524m
Ri = 0.1016m

For Th=Tc at output, length of pipe would have to be 3m

For Tho= 40 °C, a drop of 10 °C, total length of 1.25m, much more feasible.

Appendix C

Samples of dog food, wood chips, wet wood chips and compost mixture were collected and weighed in the lab. The samples were then dried according to the TMECC guidelines (Thompson et al., 2002) to determine their moisture content.

Table 3: Measured values and moisture content analysis

Material	*Initial Sample Weight [a] (g)*	*Sample Weight After 24-hr drying (g)*	*Moisture Content, wet basis (Stnd. Dev.[b])*
Dog food	8.77	8.00	8.8 (0.3)
Wood chips	3.81	3.18	16.5 (0.2)
Wet wood chips	11.03	5.16	53.8 (4.9)

Statistics are based on a sample size of n=3 measurements.
[a] Values in the table are the direct measurements obtained from the lab analysis.
[b] Stnd. Dev. = Standard deviation

Table 4: Analysis of Compost Mixture Samples

	Initial Mass (g)	*After 24-hr Drying (g)*	*After 5 hrs in furnace (g)*	*MC[a] Wet Basis (Stnd. Dev.[b]) %*	*Total Solids (Stnd. Dev.) %*	*Volatile Solids % of TS*	*Ash Content (Stnd. Dev.) %*
Compost Mixture	21.70	8.06	0.51	62.5 (4.4)	37.4 (4.4)	93.7	6.3 (0.8)

Statistics are based on a sample size of n=6 measurements.
[a] MC = Moisture Content
[b] Stnd. Dev. = Standard deviation

Appendix D

DETERMINING DENSITIES OF COMPOST INGREDIENTS AND COMPOST MIXTURE.

Samples of the compost mixture and its individual ingredients were taken and analyzed to determine their densities. The results are presented in the table below.

Table 5: Density Measurements

	Mass without Crucible *g*	Volume of empty crucible *L*	Density (Stnd. Dev.) [a] *kg/m³*
Dog Food	34.1	0.10	341.3 (29.4)
Wood Chips	27.5	0.17	162.5 (12.7)
Compost Mixture	49.3	0.08	589.9 (138.8)

Statistics are based on a sample size of n=3 measurements.
[a] Stnd. Dev. = Standard deviation