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ANAEROBIC PHASED SOLIDS DIGESTER PILOT DEMONSTRATION PROJECT

Biodegradability and Soil Amendment Potential of Anaerobically Digested Residues

PIER INTERIM PROJECT REPORT

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California Energy Commission
Public Interest Energy Research Program

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DISCLAIMER

Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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- Transportation

This report is the interim report for the Anaerobic Phased Solids Digester Pilot Demonstration project (contract number 500-02-004) conducted by University of California, Davis and Onsite Power Systems, Inc. The information from this project contributes to PIER's Renewable Energy Technologies Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

Table of Contents

List of Figures

Abstract

The elemental composition of fresh and digested food and green waste were measured. The suitability of these materials as soil amendments was evaluated. Stability of digested and composted food and green wastes were also experimentally determined in terms of respiratory quotient (RQ) and maximum carbon dioxide evolution index (MCI). Results showed that the concentration of many elements in the food and grass waste increased, as percentage of total solid contents of materials, during digestion but the nutrient content within the system did not change. The heavy metal content of both green and food wastes increased during digestion. The digested food waste had ammonia to nitrate ratio of 52.5 and the digested grass waste had a ratio of 65.0. The C/N ratio of the digested residues was less than 25. Based on the ammonia/nitrate ratio, the fresh and digested food and green wastes were classified as immature materials to be used as soil conditioners. However, based on the C/N ratio, using these digestates would not negatively affect the plant growth. The RQ was approximately 0.6 for the digested grass and food wastes and the composted food waste. The RQ of the composted green waste was 0.39 and the potting soil was 0.12. The results of the MCI showed that the digested food waste was unstable. While composted food wastes and the digested grass waste were stable and the composted green wastes and potting soil were very stable.

Executive Summary

Organic waste (e.g., food and green wastes) are an important source of plants nutrients. Therefore they could be used in the horticulture industry. However, the characteristics of these materials depend on the technology used for waste processing. Anaerobic digestion and composting are the two common technologies applied for treatment of different organic wastes. Anaerobic digestion provides many sustainable and environmental benefits. However, the stability characteristics of the digestate depend on the operational conditions of the anaerobic digestion system. In many cases, the digestate needs to be post treated to produce stabilized material: a material that is hard to be further biodegraded. The Anaerobic Phased Solids (APS) Digester system was developed at the University of California, Davis to treat organic solid wastes for biogas production. The objective of this project was to evaluate the nutrient contents and the stability of the digested food and green wastes. The biodegradation stability of the digestates and the compost produced from these digestates were experimentally determined by measuring carbon dioxide evolution and oxygen consumption. Respiratory quotient (RQ) and maximum carbon dioxide evolution index (MCI) were determined.

The results of elemental analysis showed that N, P, K and Ca were the major elements in both fresh and digested food and green wastes. Concentration of many elements (as % of dry matter) increased during digestion, most likely because all of the elements are nonorganic and the volatile solids are undergone degradation and converted into biogas and therefore they decreased during digestion but the nutrients content within the system did not decrease. The concentration of nitrogen and potassium decreased after digestion probably because they are soluble ions so that they were dissolved in the liquid medium that remained in the APS Digester. The concentration of heavy metals also increased during digestion. However, their concentrations were still significantly below the US Biosolids limit, set in EPA rule 503. The total concentration of available nitrogen in both digested food waste and digested green waste exceeded the level of 300 mg/l. The pH is 8.6 for the digested food waste and 7.6 for the digested grass waste. After two weeks of aerobic composting with peat moss the pH dropped to 7.2 and 7.1, respectively. These pH values are higher than the recommended pH values (6-7) for potting mixes. The total carbon concentration was 47.2% for the digested food waste and 42.7% for the digested grass waste. These values are within the satisfactory limit. The electrical conductivity (EC) was 2.44 and 1.88 dS/m for the digested food waste and digested green waste, respectively. The recommended electrical conductivity of potting soils should be below 2.0 dS/m (in a 1:1.5 dilution). The ammonia/nitrate ratio was 52.5 and 65.0 for digested food waste and digested grass waste. The C/N was less than 25 for both digested wastes. Based on the ammonia/nitrate ratio ratios, the fresh and

digested food and green wastes are classified as immature materials to be used as organic based fertilizers. However, based on the C/N ratio, using these materials would not negatively affect the plant growth.

The carbon dioxide evolution, oxygen consumption, respiratory quotient (RQ), maximum carbon dioxide evolution index (MCI), and Dynamic Respiration Index (DRI) were determined for composted and digested samples of both food and green waste. Dynamic respirometry tests were carried out under a controlled temperature (34^{o}C). A potting soil mix (1:1 peat and vermiculite on a volume basis) was used as a control. The anaerobic residues produced more CO_2 than their aerobic counterparts. The composted food waste, though, produced more CO_2 than the digested green waste. The digested food waste, composted food waste and digested green waste all reached their maximum rate of CO_2 evolution within the first two days of the experiment. The O_2 consumption profiles look almost identical to the CO_2 evolution. The RQ was approximately 0.6 for the digested grass and food wastes and the composted food waste. The RQ of the composted green waste was 0.39 and the potting soil was 0.12. Digested food waste had the highest values of MCI and DRI. This material was considered to be unstable based on the recommended values of MCI and DRI. Other materials were considered stable from biodegradability point of view.

Biodegradability and Soil Amendment Potential of Anaerobically Digested Residues

1. Introduction

The U.S. generated 251.3 million tons of municipal solid waste; 162.9 million tons of this waste was organic matter in 2006 (EPA, 2006). About 66.1 million tons of the organic waste was recovered, either through composting, recycling or combustion for energy generation. Given current tipping fees of $25 per ton, the 96.8 million tons of land-filled organic matter is equivalent to 2.4 billion dollars of wasted revenue (Zhang, 2007). In landfills, organic matter takes up space and releases methane; when added as a soil amendment, it can help reduce erosion, reduce fertilizer usage, and increase crop yields (Atiyeh et al., 2000; Golueke, 1972; Hoitink, 1997; Martin, 1992).

Anaerobic digestion is an alternative method of organic matter decomposition to aerobic composting. Anaerobic digestion is a biochemical process to convert the organic substrates into methane and hydrogen. The benefits of anaerobic digestion are production of biogas, a renewable energy source, reduced greenhouse gas emissions, and the possible byproduct of a soil amendment. Anaerobic digestion typically converts about 50-75% of the initial total solids to gaseous form, leaving 25-50% as anaerobically digested solid residues (Zhang, 2006). Anaerobically digested residues have been reported to have excellent fertilizing properties, increase soil organic matter content, and decrease plant pathogen populations (Bath and Ramert, 1999; Dahiya and Vasudevan, 1986; Garg et al., 2005; Mehta and Daftardar, 1984; Salminen et al., 2001; Shen, 1997; Shenlin, 1992; Veeken, 2005; Vermeulen et al., 1993).

Historically, anaerobic composts were among the first mechanized composting processes; the Beccari process combines an anaerobic stage in an enclosed reactor with gradual venting to the final aerobic stage, and was first patented in 1920 (Golueke, 1972). Crops grown with anaerobically digested residues have been shown to have higher yields than with aerobic compost, mainly due to its higher mineral nitrogen content (Bath and Ramert, 1999). Both aerobic composts and anaerobically digested residues have been reported to prevent disease in horticultural crops (Hoitink, 1997; Jingru, 1992). In one study, biogas residues resulted in higher yields and grain quality for wheat and barley than aerobic composts for the same amount of nitrogen applied (Svensson et al., 2004).

Anaerobically digested composts may have different qualities than their aerobic counterparts, which may make them more or less suitable for potting media. Some research has been done on processing anaerobically digested paper and kitchen wastes into plant growth substrates, but a full comparison of the aerobic and anaerobic pathways has not been completed (Vermeulen et al., 1993). A comprehensive nutrient and heavy metal content analysis of anaerobically digested residues is essential to widespread agricultural adoption of these residues. Carbon to nitrogen ratios should ideally be 25:1 to allow nitrogen mineralization after soil incorporation (Martin, 1992). Aerobic composting can have large amounts of ammonia volatilization, which reduces the nitrogen fertilizer in the final product (Kirchmann and Witter, 1989). Anaerobic digestion has the potential to increase the amount of mineral nitrogen in the residue, as compared to aerobic composting. Excess mineral nutrients, such as calcium, potassium, or magnesium, can present a salinity problem for both aerobic and anaerobic composts. However, excess salts in compost used for horticultural purposes can be alleviated with leaching (Chong, 2005). Nevertheless, saline organic wastes used to amend mineral soils can salinize both soil and groundwater, if appropriate rates are exceeded (Hao, 2003). At present in the U.S., heavy metal content of composts must meet the regulatory limits for biosolids. Compared to European standards, the US heavy metals limit is approximately twenty times as high (Brinton, 2000).

Stability is an important criterion in the evaluation of biogas residues as potential soil amendments. Stability is the degree to which the biodegradable organic matter will resist further decomposition, and can be determined by a variety of measurements, including CO_2 production, O_2 consumption, Dewar self-heating tests, or ammonia to nitrate ratios (Brinton, 2000; Gomez et al., 2006). Dynamic respirometry is the technique of measuring the changes in CO_2 production and O_2 consumption over a specified time interval, ranging from 3 days to 2 weeks. By comparing the maximum rates with published standards, a compost or soil amendment can be classified as stable or unstable (Brinton, 2000). Maturity is the level of completeness of the composting process. Seed germination, growth tests, and tests for the absence of phytotoxic compounds can all be used to determine the maturity level (Brinton, 2000). Stability is correlated with maturity, and many composting facilities use it as a proxy measure of maturity. By measuring the stability of the anaerobically digested residues, it will be possible to predict whether an aerobic post-treatment process will be necessary to achieve a high-quality soil amendment.

Most of the published data, on using the digested materials as soil amendments, are from digesters treating liquid substrates. However, digestion of solid and semi-solid substrates has a great importance from economical and environmental points of view. The Anaerobic Phased Digester (APS-Digester) system is a two stage system capable of digesting solid feed-stocks, and is fully described by (Zhang, 2006) and Zhang and Zhang (1999). The digested materials could be applied as soil amendments. Key areas that must be investigated for agriculture to begin using biogas residues as fertilizer are: uniformity and reproducibility of nutrient content, physical properties analysis, stability, demonstration of lack of phytotoxicity with plant growth trials, and analysis for heavy metals and other toxins.

The first objective of this study was to evaluate the nutrients and heavy metals contents of the digested food and green wastes. The second objective was to measure the biochemical stability of the compost produced from anaerobically digested food and green wastes.

2. Materials and Methods

2.1. Food and green wastes

Fresh food waste, food compost and green-waste compost were supplied by NorCal Waste Systems (Dixon, CA). The food waste used for digestion and composting was similar and collected from San Francisco by NorCal Waste Systems. The initial total solid of the food waste was 30.9%, on a wet basis (w.b.), and the volatile solids to total solids ratio (VS/TS) was 87%.

NorCal Waste Systems prepared the aerobic composts by first grinding up food and green waste with an industrial-sized grinder. The ground food waste was mixed with ground pallets for composting. The ground green-waste was not mixed with other wastes before composting. The ground material was placed in plastic bags with forced aeration (Ag-Bag Composting Technology, Ag Bags International Ltd., St. Nazianz, WI). After sixty days, the compost was removed and was allowed to cure for thirty days in windrows before sampling occurred.

The green waste samples used for anaerobic digestion were taken from UC Davis lawn clippings. The initial total solid (TS) of the grass waste was 27.4% (w.b.) and the VS/TS ratio was 78%. The grass waste is representative of the process of screening of fresh green waste for use in the digester, since the large size of un-composted wood chips would be unacceptable for the digester’s pumping system. Although the digested and composted feed-stocks were not identical, the finished composts and digested residues were representative of the final product farmers or horticulturalists would receive.

2.2 Digestion system

A laboratory-scale Anaerobic Phased Solids (APS) digester system was used to process food and green waste, as described by Zhang (2006). The digester system consisted of four hydrolysis reactors and one biogasification reactor, with working volumes of 1 L and 3.7 L, respectively. During digestion, liquid was circulated once every two hours to transport the fermented feedstock to the biogasification reactor. Food and green wastes were digested for 12 days each, at 55°C. The solid food and grass residues were removed manually from the digester and new batches of food and grass wastes were loaded. The solid residues were stored at 4°C for 1-3 months until the respirometry experiment.

2.3 Particle size distribution

Due to their larger particle size, the digested residuals were briefly ground in a blender to achieve similar particle sizes as the corresponding aerobic compost (Figure 1). The particle size distribution of the digested residuals was measured using nested sieves at an approximate moisture content of 10%. The digested grass waste has a smaller particle size than the composted green waste, especially in the <0.05 mm and >2 mm range. The pH of the digested and composted wastes was measured using 1:5 slurry as described in standard test methods (Thompson, 2002).

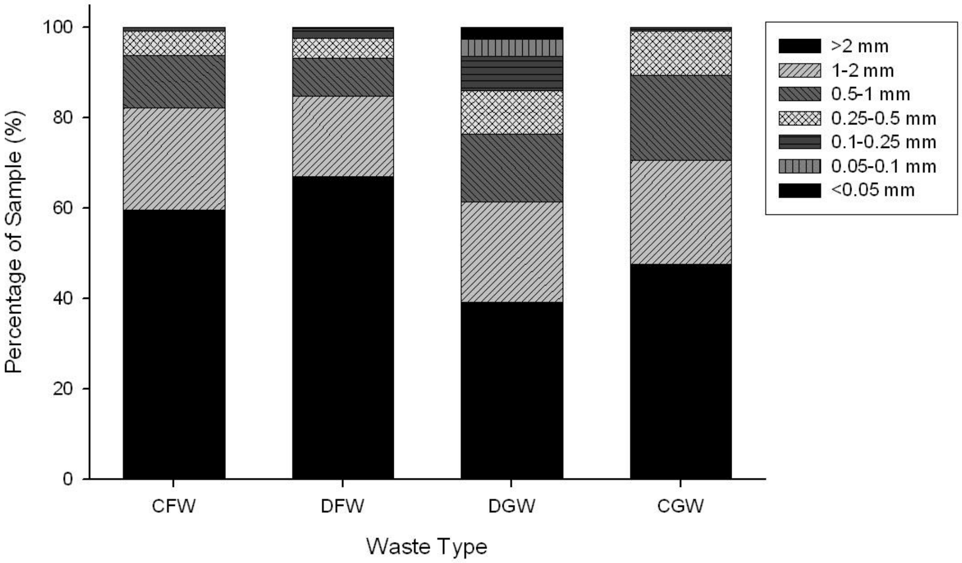

Figure 1. The particle size distribution for different materials. Composted food waste (CFW), digested food waste (DFW), digested grass waste (DGW) and composted green waste (CGW).

2.4 Carbon dioxide and oxygen consumption measurements

The carbon dioxide evolution and oxygen consumption of composted and digested samples of both food and green wastes was measured by dynamic respirometry. A potting soil mix (1:1 peat and vermiculite on a volume basis) was used as a control. All digested residuals, composts, and potting soils were stored at 4°C until the testing began.

Each waste was mixed with the potting soil in a 1:1 ratio, on a dry weight basis (d.b.). The moisture content of the mixes was determined by drying the samples at 70°C for 24 hours. The mixtures were adjusted to approximately 60% moisture content (d.b.).

The mixtures were allowed to equilibrate at 4°C overnight. The moisture contents at the beginning and end of the respirometry experiment are shown in Table 1.

Table 1. The initial and final moisture content of the 1:1 mix, final pH of the 1:1 mix, the final bulk density of the mix, and the initial VS/TS ratio of each type of waste with potting soil.

Organic Media	Initial Moisture Content (%)	Final Moisture Content (%)	Final Bulk Density (g/cm^3)	Final pH	VS/TS Ratio
Potting Soil	59.6	57.9	0.089	6.9	0.34
Digested Food	57.1	60.3	0.116	7.2	0.55
Food Compost	60.0	59.8	0.121	6.8	0.47
Digested Grass	56.2	58.8	0.084	7.1	0.54
Green Compost	57.1	58.4	0.121	6.8	0.41

For anaerobic digestion, three replicate 25 g (dry weight) samples of the potting mix control or 1:1 mixtures of potting mix and either digested food, digested grass, composted food, composted green waste were loaded into 250 mL, 7 cm diameter reactors and placed in an incubator (Istotemp Incubator, Fisher Scientific) at 35°C for two weeks. An unfilled reactor was included to measure background levels of oxygen and carbon dioxide. A schematic of the respirometry experiment system is shown in Figure 2. A flowmeter (RateMaster Flowmeter, Dwyer Instruments) maintained a forced air-flow of 20 mL/min through the sixteen reactors. The flow rates were measured every 2 to 3 days throughout the experiment using a mass flow meter (Humonics Veri-flow 500, J & W Instruments). A chamber identical to the reaction vessels was filled with water to create a bubbler, which humidified the air before it reached the flowmeter. After passing through each sample, the air was dehumidified with a molecular sieve. A 16-position multiposition valve (VICI Valco, Houston, TX) was used to pass exhaust air from each reactor through CO_2 and O_2 sensors. The valve was switched every 20 minutes, so that each reactor was sampled once during 320-minute cycles. Oxygen concentrations were measured using a Zirconia oxide oxygen sensor (Neuwghent Technologies, LaGrangeville, NY), and carbon dioxide concentrations were measured using an infrared CO_2 sensor (Vaisala, Suffolk, UK).

The flowmeter maintained the flow of air to the 16 sample reactors at approximately 20 mL/min. The multi-position valve allowed the data acquisition system to measure the CO_2 and O_2 concentrations for each reactor for twenty minutes. Each reactor was measured once during a 5 hour, 20 minute cycle. The data acquisition system (LabTechpro Build Time, Laboratory Techologies Corp., Inc.) recorded the average molar concentration of CO_2 and O_2 over the twenty-minute intervals for each reactor.

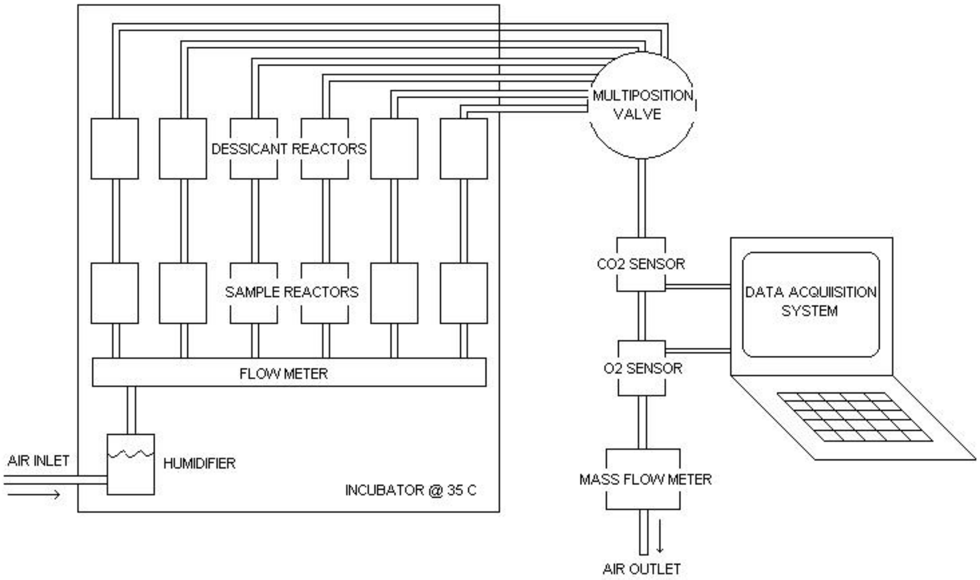

Figure 2. Schematic of the set-up for the respirometry experiment.

The carbon dioxide evolution and oxygen consumption were calculated from the difference in carbon dioxide and oxygen concentration, respectively, between the reactors with samples and the blank reactor. The carbon dioxide evolution rates (CER) and oxygen uptake rates (OUR) were calculated by using the following equations:

$$CER = F(CO_{2out} - CO_{2in}) / g_{V.S.}$$
$$OUR = F(O_{2out} - O_{2in}) / g_{V.S.}$$

where F is the air flow rate (mg air/day), $CO_{2,out}$ is the concentration in the outgoing air (mg CO_2 /mg air), $CO_{2,in}$ is the concentration of carbon dioxide in the incoming air from the blank reactor (McEachin and VanderGheynst, 2006), $O_{2,in}$ and $O_{2,out}$ are the respective concentrations of oxygen in the incoming and outgoing air (mg O_2 /mg air). The dynamic respiratory index (DRI) was calculated by averaging the oxygen consumption rate over the 24-hour period with the greatest biological activity (Scaglia et al., 2000). The maximum carbon dioxide evolution index (MCI) was calculated similarly, by averaging the CO_2 evolution rate over the 24-hour period with the highest rates, although the rates are typically compared on a per day basis (Brinton, 2000).

2.5 Data analysis

The DRI and MCI were analyzed by a one-factor ANOVA method using Excel software 2003. The cumulative CO_2 evolution and O_2 production were also analyzed using a one-factor ANOVA. The differences in each of the treatments were compared using Tukey's test at $\alpha = 0.05$.

3. Results and Discussion

3.1 Element contents

Many of the elements in the food and grass wastes increased in concentration (based on the dry solids) during digestion, most likely because all of the elements are nonorganic and the volatile solids are undergone degradation and converted into biogas and therefore they decreased during digestion. But the nutrient content within the system did not decrease (Table 2). During solid extraction from the digester effluent, a large proportion of insoluble nutrients will stay with the solid residue. The nitrogen content decreased in the digested food waste, and the potassium decreased in both the digested solid fraction of food and green wastes. The decrease of nitrogen and potassium could have been caused by these more soluble ions dissolving in the liquid medium that remained in the APS Digester. The large increase of aluminum and iron during digestion may have resulted from interaction of the bacteria and Archaea with metal components of the APS Digester. Sulfate-reducing bacteria have been shown to corrode iron and aluminum in anaerobic environments; sulfate reduction could have occurred at the beginning of digestion (Hamilton, 1985).

Table 2. The elemental content (% of dry solids) of the fresh and digested food and green waste is shown.

Element	Food Waste		Green Waste		Percent Increase	
(%)	Fresh	Digested	Fresh	Digested	Food	Green
Nitrogen	3.16	1.94	2.56	2.88	-39	13
Phosphorus	0.52	0.58	0.52	0.63	12	21
Potassium	0.90	0.52	2.22	0.89	-42	-60
Calcium	2.16	2.83	1.06	1.71	31	61
Magnesium	0.14	0.19	0.45	0.55	41	22
Sulphur	0.25	0.30	0.37	0.45	19	23
Aluminum	0.12	0.63	0.03	0.11	425	317
Iron	0.08	0.71	0.04	0.15	829	327

The heavy metal content of both green and food wastes increased during digestion (Table 3). The US Biosolids limits from EPA rule 503 (also applied to land application of processed sewage sludge) are shown in Table 3 as well as the recommended maximum for intensive compost use with vegetables (Brinton, 2000).

The final heavy metal content is still significantly below the US Biosolids limit, set in EPA rule 503, which is the only legal limit on heavy metals in compost in the U.S. (Brinton, 2000). When judged against the German Agriculture and Horticultural

Association standards for heavy metal in intensive vegetable production (Table 3), the heavy metal content was low enough to allow intensive use in vegetable production, except for the nickel and zinc content in the digested food waste, and the copper content in both types of waste.

Table 3. The heavy metal content (mg/L) of the fresh and digested food and green waste.

Heavy Metal	Food Waste (mg/L)		Green Waste (mg/L)		Bio-solids Limit (mg/L)	Intensive Use (mg/L)	Percent Increase	
	Fresh	Digest	Fresh	Digest			Food	Green
B	11	18	24	131	NA	NA	60	446
Cd	<1	<1	<1	<1	39	0.75	NA	NA
Cr	2.5	13.2	2.0	9.7	1200	75	428	397
Cu	31	107	14	107	1500	50	245	644
Pb	4	27	6	10	300	75	657	67
Mn	60	84	54	102	NA	NA	41	91
Ni	2	51	7	16	420	30	2425	129
Zn	76	266	38	154	2800	200	249	305

3.2 Compost suitability

The compost suitability parameters for the fresh and digested food and green waste are shown in Table 4. The total concentration of available nitrogen in both digested food waste and digested green waste exceeded the 300 mg/l level recommended by Wood's End Laboratory (Brinton, 2000). The pH is 8.6 for the digested food waste and 7.6 for the digested grass waste, although the pH decreased to 7.2 and 7.1, respectively, after two weeks of aerobic composting with peat moss, as indicated in Table 2. The pH is recommended for potting mixes to be between 6 and 7, and both residues are higher than this recommendation (Brinton, 2000). The total carbon concentration was 47.2% for the digested food waste and 42.7% for the digested grass waste. The amount of organic matter is recommended to be greater than 30%; both residues satisfy the organic matter requirement (Brinton, 2000). The electrical conductivity was not measured for the fresh food waste, but the salt content decreased during digestion for the green waste. The EC of the digested food waste was 2.44 dS/m, while the digested green waste was 1.88 dS/m. The electrical conductivity of potting soils is recommended to be below 2.0 dS/m (in a 1:1.5 dilution) to avoid salinity damage in general nursery conditions (Handreck and Black, 2002). However, excessive salts in potting media can be leached by standard irrigation procedures or by mixing with other, non-saline potting media (Chong, 2005).

The fresh and digested food and green wastes are classified as immature, using both the ammonia/nitrate parameter and the C/N parameter (Table 4). The ratio of ammonia to nitrate is a maturity parameter; the lower the ratio, the more nitrification has occurred in the compost. The digested food waste had a ratio of 52.5 and the digested grass waste had a ratio of 65.0. A ratio less than 0.5 is very mature, from 0.5-3.0 is mature, and above 3 is considered immature (Brinton, 2000). The C/N of the digested residues are both less than 25. The ratio of C/N is an indicator of maturity, and using soil amendments with a C/N greater than 25 will generally cause nitrogen draw-down and poor plant growth (Brinton, 2000).

The nutrients content of the digested wastes has the potential to replace slow-release fertilizers in a potting mix. The ammonium content in the digested food and grass wastes (525 and 650 ppm, respectively) is much higher than the recommended limit of 25 ppm in greenhouse soils (Newman, 2008). However, the nitrate content for the two wastes is <10 ppm and 10 ppm, respectively, which is lower than the recommended minimum of 25 ppm (Newman, 2008). Aerobic processing should help correct this imbalance, since ammonia will both volatilize and be oxidized to the nitrate form. However, the negative effect of ammonia emissions during composting process should be controlled. The recommended levels of phosphorus, potassium, magnesium, calcium, and sulfur for greenhouse soils (50, 175, 4000, 500 and 50 ppm, respectively) were all exceeded by the levels in the digested food and grass waste (Newman, 2008). This problem could be corrected either by leaching, or by mixing the digested wastes with media lacking nutrients, like peat moss.

Table 4. The compost suitability parameters for the digested and fresh food and green waste.

Compost Suitability Parameters	Food Waste		Green Waste		Percent Increase	
	Fresh	Digested	Fresh	Digested	Food	Green
NH_4-N (ppm)	973	525	630	650	-46	3
NO_3-N (ppm)	118	<10	25	10	NA	-60
NH_4/NO_3	8.3	52.5	25.2	65.0	534	-52
Total Carbon (%)	46.8	47.2	41.3	42.7	1	4
C/N	14.8	24.3	16.1	14.8	64	-8
pH (H_2O 1:5)	5.78	8.65	8.05	7.62	50	-7
EC (H_2O 1:5) (dS/m)	NA	2.44	3.94	1.88	NA	-52

3.3. Respirometry Experiments

The anaerobic residues produced more CO_2 than their aerobic counterparts (Figure 3). Each curve is the average for the three reactors for each treatment and the error bars show one standard deviation. The baseline measurements are shown for the day before the experiment. The experiment begins at day 0. Each data point represents a ten hour period.

The composted food waste, though, produced more CO_2 than the digested green waste. The total cumulative CO_2 evolution for each reactor was analyzed using a one-factor ANOVA test and Tukey's test, at $\alpha = 0.05$. All treatments had significantly different cumulative evolutions, except between the composted green waste and the potting soil.

The digested food waste, composted food waste and digested green waste all reached their maximum rate of CO_2 evolution within the first two days of the experiment (Figure 4). Each curve is the average for the three reactors for each treatment and the error bars show one standard deviation**.** The large error in the first day is due to slightly different lag times for each reactor.
The lag times, or the time before the maximum rate is achieved, varied between the three treatments. The digested grass waste had the shortest lag time, followed by the digested food waste and the composted food waste. This indicates that readily degradable compounds were present in both of the digested wastes. The rates of carbon dioxide evolution peaked twice for the digested and composted food wastes, and to a lesser degree for the digested grass waste. Microbial succession, or a change in the microbial populations, could possibly explain this result.

The cumulative oxygen consumption and rate of oxygen consumption are seen in Figures 5 and 6, respectively. The O_2 production profiles look almost identical to the CO_2 evolution, indicating that aerobic processes dominated during the respirometry experiment. The respiratory quotient (RQ), or ratio of CO_2 to O_2, was approximately 0.6 for the digested grass and food wastes and the composted food waste. The RQ of the composted green waste was 0.39 and the potting soil was 0.12. The RQ can vary depending on available nutrients, oxygen and the carbon substrate (Dilly, 2003; Gea et al., 2004). The RQ appears to be roughly correlated to the stability of the wastes but more research is necessary to verify this relationship.

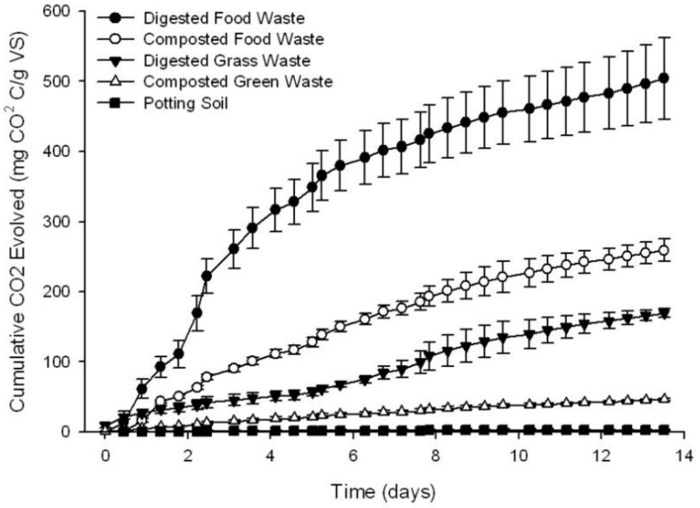

Figure 3.The cumulative CO2 produced for different materials.

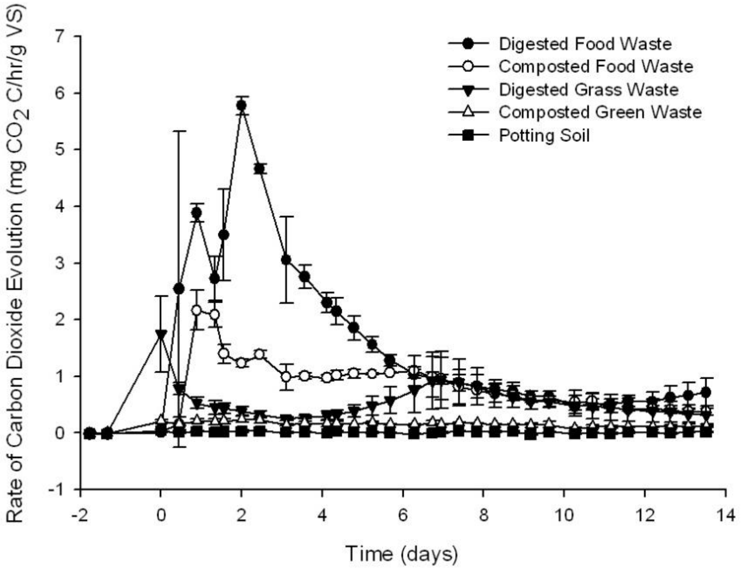

Figure 4. The average rate of carbon dioxide evolution (mg CO_2 C/hr/g V.S.) over the two week experiment.

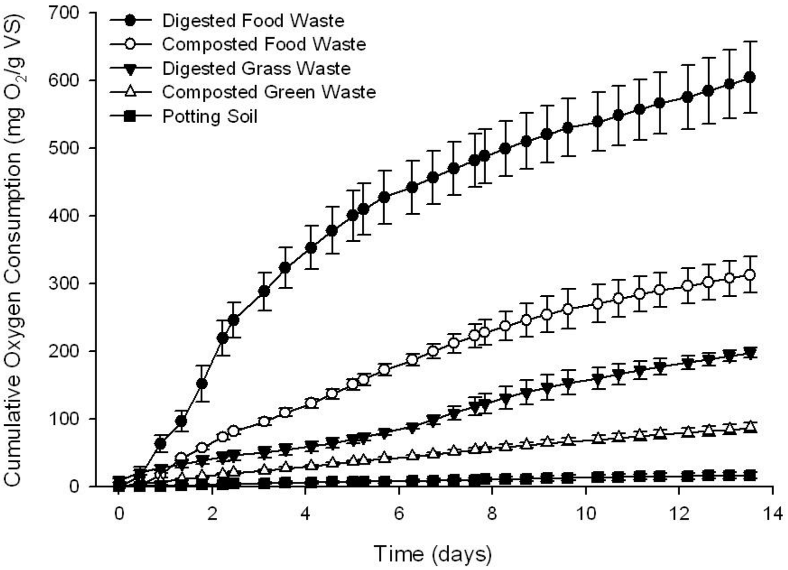

Figure 5. The cumulative oxygen consumption (mg O_2/g V.S) over the two week experiment for different materials.

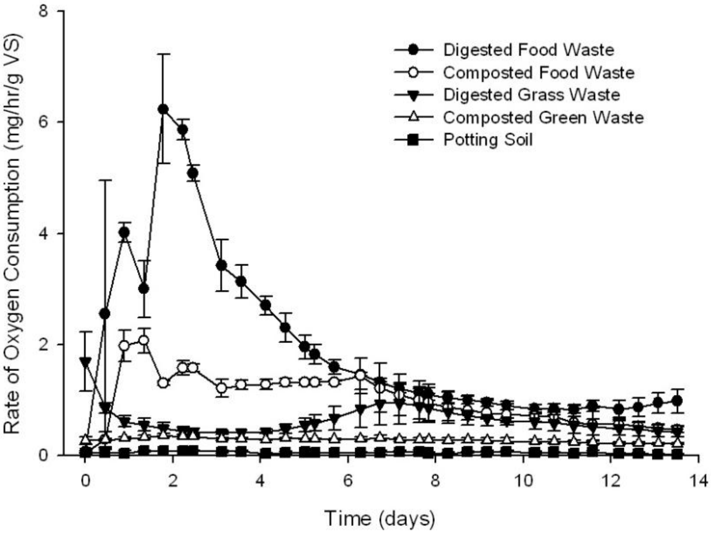

Figure 6. The average rate of oxygen consumption of the three reactors for different materials.

The maximum carbon dioxide evolution index (MCI) is shown in Figure 7, and the Dynamic Respiration Index (DRI) is shown in Figure 8.The measured MCI values were 32.8, 12.7, 7.7, 1.5 and 0.2 mg CO_2 C/day/gVS for digested food waste, composted food waste, digested grass waste, composted green waste and potting soil, respectively. The measured DRI values were 5.7, 1.9, 1.0, 0.4 and 0.1 mg O_2/hr/g VS for digested food waste, composted food waste, digested grass waste, composted green waste and potting soil, respectively

The conditions of the experiment (temperature, pH, pre-incubation time, air flow rate, and moisture content) affect both indices and makes comparison with existing standards difficult. Wood's End considers an MCI greater than 14 mg CO_2/day/g V.S. to be unstable, and below 2 mg CO_2/day/g V.S. to be very stable (Brinton, 2000). Since temperature has the largest effect on the index, and the Wood's End tests are carried out at 34°C, these standards may be the most applicable (ADAS, 2005). Using those standards, the digested food waste is classified as unstable, while the composted food waste and digested grass waste are stable, and the composted green waste and potting soil are both very stable.

Wood's End considers a DRI for oxygen above 2 mg O/hr/g VS to be unstable, and below 0.5 to be very stable (Brinton, 2000). By the DRI, the composted food waste is also considered unstable, while the other classifications remained the same. Using different index standards for the MCI (of >8 mg CO_2/day/g V.S. is unstable and < 2 mg CO_2/day/g V.S is stable), the classifications for both DRI and MCI would have been equivalent (Brinton, 2000).

The digested food waste is unstable, while the composted food waste and digested grass waste are stable, and the composted green waste and potting soil are very stable.

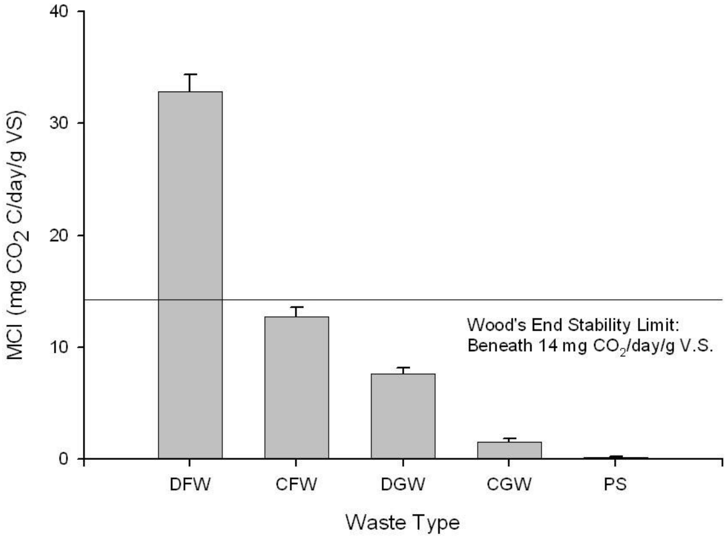

Figure 7. The maximum carbon dioxide evolution index (MCI) for different materials.

Digested food waste (DFW), composted food waste (CFW), digested grass waste (DGW), composted green waste (CGW) and potting soil (PS).

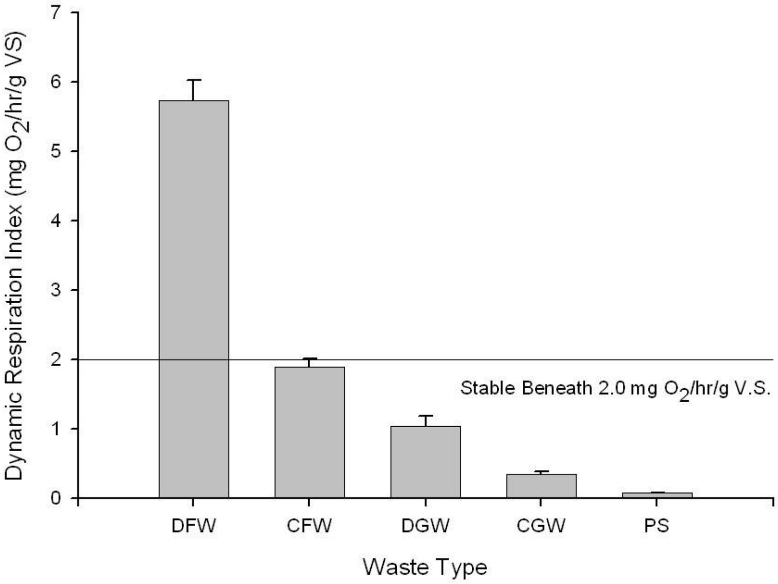

Figure 8. The Dynamic Respiration Index (DRI) for different materials.

Digested food waste (DFW), composted food waste (CFW), digested grass waste (DGW), composted green waste (CGW) and potting soil (PS).

4. Conclusions

The digested food waste was found to be unstable and immature. The digested grass waste would be considered stable using respirometry techniques, but the ratio of ammonia to nitrate indicates that the digested waste was still not mature. Both of the anaerobically digested residues would need aerobic post-processing. The high salinity is a cause for concern, but not an insurmountable problem. The heavy metal content is low enough to allow legal use in the U.S.; however the levels of nickel, zinc and copper may restrict use of the digested residues in intensive, vegetable production. The respirometry experiment provided valuable data on the stability of the different wastes and their composting potential, but evaluation of the experimental set-up with other stability tests, like the Solvita test and the Dewar Self-Heating test, is needed. Reproducibility, uniformity and physical properties of the digested residues are all areas worth investigation. Finally, plant growth trials are needed to fully evaluate the potential of residues as soil amendments.

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