October 11, 2010

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TC 25109

Mr. Jeff Callahan
Manager
Resource Conservation Division
1901 63rd Street
Boulder, CO 80306

Subject: Final Organic Waste Management Feasibility Evaluation Report for Boulder County, Colorado

Reference: Contract No. 5063-08

With this letter, Tetra Tech, Inc. (Tetra Tech) is submitting the Final Organic Waste Management Feasibility Evaluation Report for Boulder County, Colorado. This report indentifies viable organic waste management technologies for Boulder County and presents preliminary evaluations of environmental and economic impacts associated with each technology. This report concludes with a summary and recommendations for future organic waste management activities for the county.

For any questions or comments related to this report, please contact the undersigned at (719) 685-6586 or via e-mail benjamin.recker@tetratech.com.

Sincerely,

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Attachment: as stated

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Boulder County
Resource Conservation Division

Final Organic Waste Management Feasibility Evaluation Report for Boulder County, Colorado

October 11, 2010

Submitted to:

Mr. Jeff Callahan
Manager
Resource Conservation Division
1901 63rd Street
Boulder, CO 80306

Submitted by:

Tetra Tech, Inc.
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EXECUTIVE SUMMARY

Boulder County has established itself as a national leader in promoting and implementing progressive waste management practices and maximizing waste diversion. In November 2005, the Boulder County Commissioners adopted Resolution 2005-138, "Adopting Zero Waste as a Guiding Principle and Supporting the Creation of a Zero Waste Plan," which clearly establishes the waste management goals for the county. Based on the zero waste goal, Boulder County has invested significant resources to implement comprehensive waste management and minimization programs including a comprehensive pay-as-you-throw (PAYT) ordinance that includes single steam and organic collection, a recycling center that processes 45,000 tons per year of single stream materials, household hazardous waste collection, education and outreach activities, and a subsidized program to manage organic waste.

This organic waste management feasibility evaluation was developed to support organic waste management planning in Boulder County. This feasibility evaluation provides a preliminary analysis of various alternative organic waste management technologies so Boulder County decision makers can discard certain technologies from future consideration and focus future organic waste management efforts considering the technical and economic considerations presented in this report. This feasibility evaluation was conducted in three steps. The first step determined the types and approximate volumes of organic waste generated and available as feedstock for an alternative waste management program. Based on EPA estimated organic waste generation rates and current organic waste management practices, it was assumed that 32,350 tons of organic waste per year could be managed and processed by the county.

The second step identified and evaluated alternative waste management approaches and technologies to convert the identified waste streams into a stable organic product and/or energy. For this feasibility evaluation, composting, anaerobic digestion, integrated anaerobic digestion and composting, and gasification organic waste management systems were assessed. Although composting is not a renewable energy technology, it offers relatively lower initial capital costs, waste minimization, and a useable/saleable end-product. The other key advantages of composting are that the technology has a self-contained footprint, ability to be located in close proximity to highly sensitive receptors (the general public), and it is a low risk/robust technology. Equipment and labor availability, climate changes, and control of public health and nuisance factors are possibly considered the disadvantages of this technology. Anaerobic digestion and gasification processes offer renewable energy production with a compact and self-contained footprint. Advantages that can be realized by both of these technologies include decreasing both Boulder County's electrical and thermal costs due to renewable energy potential, minimizing wastes, and offsetting disposal requirements/costs. Both gasification and anaerobic digestion technologies are capital intensive as compared to composting. Gasification technology has usually higher capital costs, operation and maintenance costs, and process risks as compared to the anaerobic digestion, however; the return on investment is possibly higher than other options evaluated due to its high process efficiency.

Finally, the third step evaluated the potential economic costs and benefits of each alternative organic waste management technologies. For each technology, the potential capital and operating costs were determined based on the estimated 32,350 tons per year capacity. In addition to cost, potential revenue associated with each technology was estimated. Potential revenue includes tipping fees, sale of compost, energy saving/sale, and renewable energy credits depending on technology end products. An additional economic analysis was performed for each technology that assumed 10,000 tons per year throughput capacity which would reduce initial capital costs and risk associated with creating a new facility. The following tables summarize the results of the economic analysis for both 32,350 and 10,000 ton per year alternative organic waste processing facilities. Section 6 of this feasibility evaluation provides specific recommendations for future organic waste management activities in Boulder County.

Summary of Economic Analysis for 32,350 Ton per Year Facility

Technology	Capital Cost	Annual Operating Cost	Revenue
Composting			
Windrow	$1,290,000 - $1,941,000	$485,000 - $841,000	$1,855,850
Enclosed Windrow	$3,235,000 - $4,853,000	$647,000 - $1,294,000	$1,855,850
Aerated Static Pile	$2,426,000 - $4,044,000	$323,500 - $2,265,000	$1,855,850
Enclosed Static Pile(Ag-Bag)	$1,618,000 - $2,426,000	$1,294,000 - $2,265,000	$1,855,850
In-vessel	$9,705,000 - $16,175,000	$3,235,000 - $9,058,000	$1,855,850
Anaerobic Digestion	$7,277,000 - $16,138,000	$1,467,100 - $2,934,200	$1,482,930 - $1,754,630
Gasification	$15,852,000 - $23,292,000	$2,378,000 - $3,494,000	$946,885 - $1,200,185

Summary of Economic Analysis of 10,000 Ton per Year Facility

Technology	Capital Cost	Annual Operating Cost	Revenue
Composting			
Windrow	$400,000 - $600,000	$150,000 - $260,000	$585,000
Enclosed Windrow	$1,000,000 - $1,500,000	$200,000 - $400,000	$585,000
Aerated Static Pile	$750,000 - $1,250,000	$100,000 - $700,000	$585,000
Enclosed Static Pile(Ag-Bag)	$500,000 - $750,000	$500,000 - $750,000	$585,000
In-vessel	$3,000,000 - $5,000,000	$1,000,000 - $2,800,000	$585,000
Anaerobic Digestion	$2,950,000 - $5,670,000	$680,000 - $1,130,000	$461,568 - $545,549
Gasification	$4,900,000 - $7,200,000	$735,000 - $1,080,000	$292,700 - $371,000

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1.0 INTRODUCTION

Tetra Tech Inc. (Tetra Tech) was contracted by Boulder County, Colorado (Boulder County) to perform an Organic Waste Management Feasibility Evaluation to determine the viability of alternative organic waste management practices within the county. Western Disposal currently operates a centralized organic waste drop-off/processing facility at 5880 Butte Mill Road which could serve as the location for a future alternative organic waste management facility; however, the technologies and evaluation presented in this report can be applied to alternative sites should the county decide to explore additional locations.

Tetra Tech prepared this Feasibility Evaluation Report for use by Boulder County to identify and evaluate the technical, economic, sustainability and implementation considerations for various organic waste management processing alternatives. This report includes a summary of background information; purpose of the Feasibility Evaluation; available and potential organic waste streams for processing; description of potentially viable organic waste management technologies; evaluation of advantages and disadvantages of each technology; preliminary economic evaluation for Boulder County; and recommendations for future actions.

1.1 BACKGROUND

Boulder County has established itself as a national leader in promoting and implementing progressive waste management practices and maximizing waste diversion. In November 2005, the Boulder County Commissioners adopted Resolution 2005-138, "Adopting Zero Waste as a Guiding Principle and Supporting the Creation of a Zero Waste Plan," which clearly establishes the waste management goals for the county. Based on the zero waste goal, Boulder County has invested significant resources to implement comprehensive waste management and minimization programs including a comprehensive pay-as-you-throw (PAYT) ordinance that includes single steam and organic collection, a recycling center that processes 45,000 tons per year of single stream materials, household hazardous waste collection, education and outreach activities, and a subsidized program to manage organic waste. To achieve zero waste requires a systematic approach to waste management, ongoing evaluation of program results, and identification of ways to improve program performance.

1.2 PURPOSE

The purpose of this Organic Waste Management Feasibility Evaluation Report is to serve as a planning tool for future organic waste processing in Boulder County. Included in this report are an evaluation of potentially viable organic waste management technologies and an economic analysis of applicable processing technologies.

This Feasibility Evaluation Report addresses the following overall objectives:

- Reduce the environmental footprint and organic waste stream of Boulder County;
- Diversify the Boulder County's waste management portfolio;
- Compare existing waste management technologies based on their performance, advantages, and disadvantages;
- Identify evaluation criteria of potential technologies to process organic waste materials; and
- Identify key process control steps associated with the use of the technologies to minimize impacts on the environment.

This evaluation was conducted in three steps. The first step was to determine the types and approximate volumes of organic waste streams that can be beneficially utilized within the county through various organic waste management options. The second step was to identify and evaluate organic waste management technologies to convert the waste streams into a stable organic and/or energy saving products. Finally, the third step was to identify and evaluate the economic costs and benefits of these technologies.

2.0 BOULDER COUNTY WASTE STREAM GENERATION

2.1 ORGANIC WASTE TYPES AVAILABLE

Waste stream characterization is a critical part of the feasibility evaluation because the organic fraction of the waste stream varies in physical, chemical, and biological characteristics which directly determine applicable waste management technologies from both technical and economic standpoints. Based upon the Organic Waste Generation and Management Survey (OWGMS) Report for Boulder County (Tetra Tech 2010), different waste streams were classified into their various component categories. Table 2-1 below summarizes the categories and expected organic waste generated for each category.

Table 2-1
Organic Waste Generator Category, Expected Waste, and Classification

Organic Waste Generator Category	Expected Organic Waste Stream	Waste Stream Classification
Food Service (Restaurants)	Food Waste	Primary
Schools	Food Waste	Primary
Health Care Facilities	Food Waste	Primary
Grocery Stores/Food Suppliers	Food Waste	Primary
Landscape/Tree Care	Yard Waste	Primary
Community Service	Food Waste, Various Additional	Primary
Consulting Services	Office Related Waste, Food Waste	Primary and Secondary
Animal Care/Agriculture	Animal Waste	Secondary
Manufacturing	Various	Secondary
Millwork, Wood Retail	Wood Waste	Primary
Retail	Various	Primary and Secondary
Winery/Brewery	Spent Grain, Agricultural Waste	Secondary

Upon completion of this classification process, Tetra Tech selected the primary organic waste streams as food, yard, and wood waste for quantification with respect to their mass content. In addition, Tetra Tech identified potential secondary waste streams including, but not limited to: agriculture wastes such as manure and other wastes; brewery wastes; winery wastes; and office related wastes (Tetra Tech 2010).

The following sections provide a description and characterization of the primary and secondary waste streams in Boulder County that could be feedstock for the alternative waste management processes evaluated.

2.2 PRIMARY WASTE STREAMS

As shown in Table 2-1, Tetra Tech has classified various organic waste streams for this feasibility evaluation to assist in identifying and evaluating potential organic waste processing alternatives based on the general characteristics of each potentially available waste stream. For the purposes of this evaluation, primary waste streams are generated in large quantities within the county and are readily available as feedstock for technology alternatives presented in this report. The following paragraphs discuss the primary waste streams used for this feasibility evaluation. Additional details pertaining to organic waste generation and management practices within Boulder County can be found in the OWGMS Report.

2.2.1 Food Waste

With high moisture and nutrient content, post-consumer food waste produces considerable quantities of methane during anaerobic decomposition in landfills. Methane and other gases generated from decomposition of food waste have significant environmental disadvantages. First, the decomposition process can generate foul odors. Methane has been documented in numerous studies as a greenhouse gas (GHG) that contributes to climate change that has a global warming potential of 21 compared to carbon dioxide on a 100-year lifecycle, meaning methane is 21 times more potent of a GHG (ICLEI 2008). Decomposition of food waste is the second largest source of methane in landfills (U.S. EPA, 1997; Recycled Organics, 2001b). Furthermore, the high nutrient and heavy metal loading from food waste in landfill leachate can be major contributors to groundwater and surface water pollution (Russel and Higer, 1988; Borden and Yunoschak, 1990; Assmuth and Strandberg, 1993).

Food waste is generated at nearly every facility in Boulder County from office lunch rooms to parks and residences. Restaurants, schools, health care facilities, and grocery stores are known to generate large quantities of food waste because of the nature of the services they provide. Many restaurants, schools, and other food waste generators are diverting this waste stream from landfill disposal, but several generators were not utilizing existing municipal or county organic waste processing facilities.

2.2.2 Yard Waste

Generated by the residential, commercial, and industrial sectors, the yard waste stream typically consists of a wide range of grass, leaves, and other wastes from lawns and backyard gardens. The potential impacts of yard waste are usually less, relative to food waste, in landfills. In general, the percentage and composition of the yard waste stream fluctuates seasonally (RIS 2005). The largest quantities of yard waste are generated by landscape maintenance companies and forestry activities. Large quantities of yard waste are generated within the county and most of this waste stream is being diverted using existing municipal drop-off services or through individual management practices (i.e., wood fuel, chipping).

2.2.3 Wood Waste

The wood waste stream typically is comprised of a wide variety of sources including lumber yard waste, trim, shipping pallets, pruned branches, whole trees from street and park maintenance, and other wood debris from construction and demolition activities. They are mostly used as a feedstock source for biomass fuel, mulch, and composting due to their limited reuse options (U.S. EPA 2003). Wood waste, such as pallets and lumber, is generated in large quantities within Boulder County, particularly from construction and millworks operations. All of the millworks operations within the county have established diversion programs in which this waste stream is diverted from landfill disposal, primarily by using saw dust and scraps for horse bedding. Wood waste from construction activities is managed in a variety of ways including reuse, processing at a municipal drop-off location, or landfill disposal depending on location and costs associated with the municipal drop-off location.

2.3 SECONDARY WASTE STREAMS

For the purposes of this evaluation, secondary waste streams are generated in large quantities within Boulder County, but only a portion would be readily available as feedstock for organic waste technologies presented in this report. As an example, animal waste and manure is generated in large quantities throughout the county and most generators have a diversion and management program in place. It is assumed that a portion of these generators will change management measures to utilize a new processing facility. It is assumed that the 100 tons of manure collected from the Boulder County Fair would be available for processing using the alternative technology, but this amount is much lower relative to Primary Waste Streams. The following paragraphs discuss the secondary waste streams utilized for this feasibility evaluation.

2.3.1 Agricultural and Animal Wastes

Agricultural and animal waste streams are primarily comprised of livestock and horse manure as well as pet waste. Agricultural and animal waste is generated in large quantities, particularly in unincorporated Boulder County. Due to the potential presence of pathogens, animal manure is not accepted by municipal organic waste collection and drop-off locations within Boulder County. Agricultural and animal wastes are managed in a variety of ways including hauling and processing at a commercial compost facility located outside of Boulder County, beneficial reuse as fertilizer on pasture lands, and landfill disposal. Several of the respondents to the OWGMS indicated that an organic waste processing facility within Boulder County would be beneficial to reduce hauling costs.

2.3.2 Brewery and Winery Wastes

Breweries and wineries produce a large amount of organic waste from the production and processing of beer and wine. As discussed in the OWGMS Report, brewery and wine wastes are generated in large quantities within Boulder County and most generators have established diversion programs in place to divert this waste stream from landfill disposal. Alternatives for managing these wastes in Boulder County include processing at an approved commercial compost facility or donating spent grain to local farmers for cattle feed.

2.4 QUANTIFICATION OF ORGANIC WASTE STREAMS

According to the United States Environmental Protection Agency (EPA) Municipal Solid Waste (MSW) Fact and Figures (U.S. EPA 2009), each person in the United States generates 4.5 pounds of municipal solid waste per day. Of this waste, food scraps, yard trimmings, and wood wastes account for 12.7 percent, 13.2 percent, and 6.6 percent respectively, of the waste stream (U.S. EPA 2009). Additionally, the EPA reports that of the food, yard, and wood waste generated, 2.5 percent of food waste, 64.7 percent of yard trimming, and 14.8 percent of wood packaging are recovered and not sent to a landfill for disposal (U.S. EPA 2009). While the U.S. EPA 2008 generation data is not specifically tailored to Boulder County and it is possible that Boulder County residents, on average, generate more or less than the national average, using these U.S. EPA data points allows Boulder County to assess and compare overall organic waste management programs. It should also be noted that the 2008 Municipal Solid Waste Fact and Figures specifically exclude certain waste streams such as agricultural and industrial waste.

The population of Boulder County is approximately 297,000 (Steelman 2009). Using the EPA reported MSW generation rate of 4.5 pounds per person per day, it is estimated that approximately 244,000 tons of MSW is generated each year in the county. Of this amount, 6.6 percent, or 16,104 tons, is assumed to be wood waste. Food waste is assumed to be approximately 30,988 tons, based on 12.7 percent of the total waste stream, and yard trimmings are assumed to be 32,208 tons or 13.2 percent of the waste stream. Based on these estimates, the total food, yard, and wood waste generation in Boulder County is assumed to be 79,300 tons. As discussed above, the U.S. EPA's national recovery rate for each of these waste streams is 14.8 percent for wood, 2.5 percent for food, and 64.7 percent for yard trimmings. Table 2-2 summarizes the expected wood, food, and yard waste generation and recovery for Boulder County's population and EPA published generation and recovery rates.

Table 2-2
Estimated Food, Yard, and Wood Waste Generation and Recovery Rates for Boulder County

Organic Waste Category	Generation Rate (% of Total Waste Stream)	Estimated Generation (Tons)	Recovery Rate (% of Generation)	Estimated Tons Recovered
Food Waste	12.7	30,988	2.5	775
Yard Waste	13.2	32,208	64.7	20,839
Wood Waste (Packaging)	6.6	16,104	14.8	2,393
Total	**32.5**	**79,300**		**24,007**

As shown in Table 2-2, it is estimated that Primary Waste Streams, food, yard, and wood waste, in Boulder County is approximately 79,300 tons per year. Of this amount, if Boulder County is assumed to achieve the national average for material recovery, 24,007 tons of the would be collected and processed. Boulder County and municipalities have implemented multiple organic waste management programs to recover these waste streams to date. Table 2-3 summarizes the organic material collected by each of these programs.

Table 2-3
Summary of Boulder County Organic Waste Programs

Program	Tons Collected
Boulder County and City of Boulder Yard Waste Drop-off Location (includes food waste)	6,591
Boulder County and City of Boulder Wood Waste Drop-off Location	1,715
Western Disposal Services Commercial Food Waste Collection	850
City of Boulder Curbside Organic Waste Collection Program	5,264
City of Boulder Christmas Tree Collection	89
EcoCycle Organic Waste Collection	2,800
University of Colorado at Boulder	234
City of Longmont	1,500
City of Lafayette	235
City of Louisville	1,500
City of Broomfield	2,650
City of Nederland	32
Forestry Management (Boulder County and City of Boulder only)	2,420
Total	**25,880**

Notes: This summary does not include organic waste recovery accomplished by private companies, such as landscape and tree maintenance entities who process their own waste.
This summary does not include material recovery from special events such as Peach Festival or Boulder County Fair.

As shown in Table 2-3, several municipal programs are collecting and managing a large amount of the Primary Waste Streams generated within the county. While the County and municipalities have made great strides in collecting and recovering organic waste, approximately 50,000 tons of additional materials are available for collection and processing when compared to the expected generation rates. It is possible that more Primary Waste Stream and Secondary Waste Stream materials can be collected and processed using an alternative technology.

3.0 ASSESSMENT OF ALTERNATIVE WASTE MANAGEMENT TECHNOLOGIES

Based on the available Primary and Secondary Waste Streams discussed above and experience with similar projects, Tetra Tech identified, reviewed, and evaluated potentially applicable waste management technologies for Boulder County. The primary technologies evaluated include:

1. Composting
2. Anaerobic Digestion
3. Integrated Anaerobic Digestion and Composting System, and
4. Gasification

Each technology's advantages, disadvantages, and application range are discussed in the following paragraphs.

3.1 COMPOSTING

Composting is an aerobic biological process including natural processes of decay and decomposition. In a commercial or municipal system, sufficient organic material is gathered to provide an adequate quantity of substrate to support a large and active microbial population. This population generates sufficient heat, through respiration, which in turn accelerates the decomposition process. In properly designed and operated composting facilities the temperature inside the compost can reach up to 140 degrees Fahrenheit (^{o}F). The excessive heat inside the compost can foster destruction and sterilization of pathogens and numerous types of seeds including weeds. Composting can be applied on both large and small scales with varying degrees of efficiency.

Properly operating compost systems consist of a succession of microbial processes. The process is categorized into four distinct sequential phases: heating, thermophilic decomposition, mesophilic decomposition, and maturation. In the heating phase, microbial respiration occurs in the presence of oxygen, causing the temperature in the compost to increase. As this occurs there is a change in the microbial population from those that thrive at ambient temperatures (Mesophiles) to those that prefer elevated temperatures up to around 131-140 °F (Thermophiles).

When thermophilic conditions are achieved this is referred to as the second phase or the thermophilic decomposition phase. As long as sufficient organic substrate can be metabolized, the action of the

Thermophiles continues to thrive and in turn generates sufficient thermal energy to maintain the temperatures within the thermophilic range. It is at this temperature that pathogens and seeds are destroyed and accelerated decomposition of the waste is realized. It is important to note that temperature is a function of microbial activity and heat removal from the process. Heat accumulation must be controlled during the composting process to provide optimal conditions for the microbial community and provide for the destruction of pathogens and seeds without accumulating too much heat such that microbial activity is inhibited. In practice it is necessary to turn the compost to prevent over-heating.

As the readily metabolized substrate is consumed and decreases, the microbial activity declines. In turn the rate of microbial respiration slows, the compost cools, and a new population of mesophilic microbes is reestablished. The compost has now transitioned to the third or mesophilic decomposition phase. Mesophilic microbes prefer moderate temperatures in the range of 77-104 °F. The compost remains warm and active as considerable degradation continues. The mesophilic phase of composting is typically the longest phase and supports the greatest numbers and diversity of microbes. Once all the readily degradable material has been utilized, the temperature returns to ambient conditions, and active decay ceases. At this stage the compost is usually referred to as “mature phase” because it contains relatively high levels of ammonia and other compounds that are toxic to plants. Microbial populations that are able to oxidize ammonia to nitrate are not able to survive at elevated temperature but thrive in moderate temperatures. During maturation these microbes re-colonize and phytotoxic compounds are dissipated and stabilized.

Depending upon the goals of the process and end use of compost, the mature stage can often be omitted. Where compost is spread broadly over the land as fertilizer for example, curing can often be skipped as the ammonia will dissipate to the atmosphere. However, where compost is produced as plant-growing substrate, curing and appropriate validation is essential.

The main benefits of the composting processes are a minimization in waste streams and a reduction in GHG emissions. The finished compost product at the end of the process would be used or sold as a soil amendment material in various land applications (e.g., commercial saleable or publically available compost) due to its high organic matter and low nitrogen content. Furthermore, this process would also provide tipping fee and landscape supply savings. To be sold as a commercial saleable product, the compost must be tested for pathogen reduction, pH, salinity, organic matter content, cadmium, lead, and percent of foreign matter (Chiumenti *et al*. 2005).

3.1.1 Composting Process and Design Parameters

Several parameters play an essential role in the process and design of a composting system because the presence of these factors in either excess or deficiency directly influences the conditions of microbial life and the decomposition of organic matter, which have important consequences on the success of the composting process and the quality of the finished product. In a materials balance, the following parameters should either be maintained during the composting process or calculated as design parameters:

- Temperature
- Moisture content
- Energy source
- Nutrient content
- Adequate oxygen
- Substrate porosity
- Carbon to Nitrogen ratio
- pH
- Bulk density
- Biodegradability of the raw materials (Volatile solids content), and
- Frequency of mixing and turning

The operating parameters involved in the composting process are similar to that of the anaerobic digestion process in that the process requires a 15 to 30 day retention time and moisture content between 40 to 60 percent is required. The composting process differs from the anaerobic digestion process in that the workable carbon-to-nitrogen (C:N) ratio acceptable for an efficient process is fairly broad. The suggested C:N operating range for composting is from 25:1 to 40:1. Table 3-1 evaluates how the operating and design parameters affect each other on both positive and negative impacts for a viable composting process.

Table 3-1
Composting Process and Design Parameters

Parameters	Influencing Factors	Consequences
Temperature	• Excessive Porosity • Ambient air temperature • Moisture content of mix • Volatile solids content	• Slowing compost process (too cool) • Limiting population diversity (too hot) • Impacting odor production (too hot)
Moisture content	• Low porosity • Excessive porosity • Low or high aeration • Low temperature • Low energy content	• Slowing biological activity and impeding composting process (too dry) • Impeding air flow (too wet) • Inhibiting temperature increases (too wet) • Resulting in sticky mixture (excessively wet) • Increasing viscosity of the mix • Overloading the equipment and causing stalling
Energy source	• Volatile solids content • Low moisture content • Nutrient imbalances • Balance between inerts and volatile solids	• Leading to low heat generation • Achieving inadequate temperatures • Leading to inability to deactivate pathogens • Achieving poor water evaporation
Nutrient content	• Lower pH • Higher pH • Biodegradability of nitrogen containing material	• Leading ammonia loss (excessive nitrogen) • Retarding composting rate (inadequate nitrogen) • Leading odor production (excessive nitrogen)
Adequate oxygen	• Low porosity • Excessive porosity • Low or high aeration • Moisture content of mix • Nitrate in the mix	• Leading to anaerobic conditions • Forming odorous organic acids • Forming other odorous reduced organic compounds
Substrate porosity	• Moisture content • Particle size • Bulk density	• Impeding composting process • Impeding air flow • Leading to anaerobic conditions (low porosity)

Table 3-1 (Continued)
Composting Process and Design Parameters

Parameters	Influencing Factors	Consequences
Carbon to nitrogen ratio	• Inadequate energy (carbon) source • Inadequate or excessive nitrogen • Volatile solids content	• Limiting microbial activity • Retarding composting rate (inadequate nitrogen) • Leading ammonia loss and odor production (excessive nitrogen)
pH	• Excessive nitrogen • Volatile solids content • Mixing	• Solubilizing minerals • Leading to anaerobic conditions (lower pH) • Leading ammonia loss (higher pH)
Bulk density	• Substrate porosity • Moisture content	• Slowing biological activity or impeding composting process
Biodegradability	• Energy (carbon) source • Volatile solids content	• Slowing compost process (low volatile solids content) • Limiting population diversity (low carbon source
Frequency of mixing and turning	• Temperature • Moisture content • Adequate oxygen	• Leading drying, caking, and air channeling (inadequate mixing) • Limiting temperature (excessive mixing and turning)

Sources:Chiumenti *et al*. 2005; Sylvia *et al*. 2005; Tchobanoglous *et al*. 2003.

3.1.2 Type of Composting

There are three types of composting systems currently in use in the industry including: aerated static pile, windrow and in-vessel. Aerated Static Pile Composting can be either active or passive. In active systems air is forced (positive) or pulled (negative) over a mixture of the compost material increasing the oxygen supply. In passive aerated static pile composting, natural air currents are utilized to supply oxygen to the pile. In active or passive static pile systems, the process generally occurs at slow rates, typically 21-28 days followed by a curing period of 30 days or longer. The amount of aeration and waste characterization generally limit the dimensions of the static pile, and typically pile heights range from 8 to 15 feet with twice depth of width.

To better manage the compost process and control odors, aerated static piles are covered with a layer of finished compost or wood chips, or the entire pile or significant portions of the system are enclosed (Tchobanoglous et al. 2003). Several vendors offer engineered covers for aerated static piles that allows for better moisture control, vector control as well as providing for collection and treatment of process air prior to venting. A variation of covered aerated static pile composting is Ag-bag composting, sometimes included as in-vessel composting technology in literature (City of Palo Alto 2008). Ag-bag composting involves grinding incoming organic material and placing the material into engineered bags, also called pods. Similar to covered aerated static piles, Ag-bag composting provides better control of moisture content, oxygen levels and helps control vectors (Cit of Palo Alto 2008). Aerated static pile and Ag-bag composting processes typically take one to two month composting period followed by a one to two month cure time (City of Palo Alto 2008). Engineered covers and Ag-bag systems, including covers, automated controls, aeration equipment, and filtration system, can cost between $500,000 and $800,000 for medium sized (20,000 tons per year) composting facilities (City of Palo Alto 2008), but these increase capital costs are less than buildings enclosures that are sometimes used to provide better control of moisture and temperature. Due to the lack of mechanical agitation, aerated static piles are rarely used for source separated (household) organic (SSO) waste streams.

In windrow composting, temperature control and oxygen levels are generally managed via mechanical agitation. The process involves the mixing and screening operations in long, narrow piles, or windrows (Tchobanoglous et al. 2003). To optimize the windrow composting, pile height is limited to 3 to 6 feet, and the width and depth of the windrows are 4 to 6 feet and 6 to10 feet, respectively.

Climatic impacts are significant for this process. In extremely wet climates, compost material may become too wet, which directly influences the quality of final product. In very cold climates, the process may be slow or not complete. An advantage, however, is that this system of composting can performed at a low cost. Moreover, the process typically requires the addition of bulking agents to increase the porosity of the compost; however, bulking agents can significantly increase the amount of material requiring transport (Chiumenti et al. 2005). Similar to aerated static pile, the composting period can range from one to three months, and some windrow composting operations are covered or enclosed for improved process and odor minimization (Tchobanoglous et al., 2003). While enclosed windrow composting offers increased process control, the capital cost of constructing enclosures are estimated to be approximately double the cost of standard windrow composting. The primary disadvantage of windrow composting is that the material must be agitated regularly. If the material is not agitated regularly, the microbial activity in the pile might drive rapid consumption of oxygen and thus various combinations of aerobic, facultative, and anaerobic activities might result in increased odors and methane generation (Tchobanoglous et al. 2003).

Aerated static pile and windrow composting generally require large footprints to operate effectively, which presents a challenge in locations where real estate is scarce and/or costly. Composting operations particularly require adequate aeration to prevent odor problems. Therefore, air for the composting process is provided through natural convection, forced aeration with blowers, or by turning or agitating the compost pile. The method of aeration defines the physical configuration of the compost operation. Even with aeration, odors from composting operation may be problematic for these processes. (Chiumenti et al. 2005; Sylvia et al. 2005; U.S. EPA 1999).

An alternative to aerated static pile and windrow composting is an in-vessel composting system. In-vessel systems have a much smaller footprint than the static pile or windrow methods, which reduces the overall space requirement for the facility (Chiumenti et al. 2005; Tchobanoglous et al. 2003; U.S. EPA 1999). An in-vessel system mechanically agitates the compost within closed containers and uses forced air to keep the compost aerobic. The odor control systems required for in-vessel composting are smaller than those used for static pile or windrow systems. Additionally, in-vessel composting systems have the potential to provide a high level of process control because of controlling environmental conditions such as air flow, temperature, oxygen concentration, etc., and generally offer the following overall features:

- Compost is contained within a vessel and the environmental and human impacts are more tightly controlled
- A wide range of organic wastes can be handled
- Strict process monitoring can be applied
- Thermal properties of the system generally ensure rapid and sustained heating
- Air input to the system can be well controlled, and
- Systems are generally scalable

In-vessel composting systems are relatively capital intensive, but they offer the most comprehensive control and containment options. Systems are generally suited for small to medium sized installations and have better engineering process control features. The following figure is an example flow chart for an In-vessel Aerobic Composting System (Adapted from Waste Enquiry 2000).

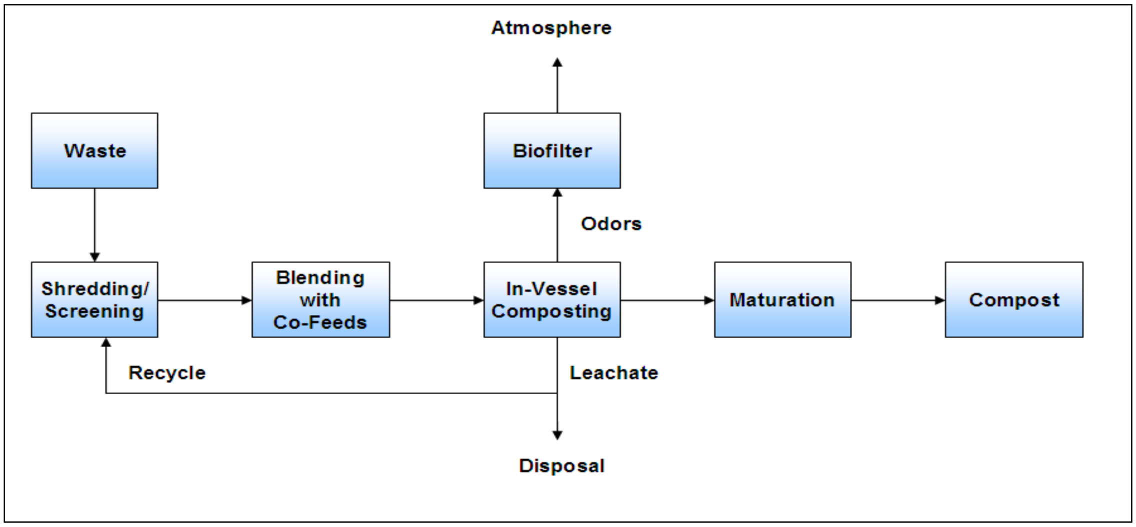

Figure 3-1
In-vessel Aerobic Composting System Flow Chart

According to a 2005 survey by NatureWorks, 154 industrial and municipal composting facilities selected have successfully been operating in the Unites States, with windrow composting being the most common (NatureWorks 2005). A-1 Organics, an organic recycling and commercial composting business in the Rocky Mountain region, has successfully operated compost facilities including the Highway 66 Facility in Plattesville, Colorado; the Rattle Ridge Facility in Keenesburg, Colorado; and the Rooney Road Facility in Golden, Colorado. A-1 Organics produces over 350,000 cubic yards of high quality compost and soil amendments per year (A-1 Organics 2010). Table 3-2 compares the three systems discussed above, and highlights key features of each type of composting process.

Table 3-2
Comparison of Composting Systems

Composting System	Advantages	Disadvantages
Aerated Static Pile	• Low capital cost • High degree of pathogen destruction • Good product stabilization • Extensive operating history both small and large scale • Adaptable to changes in bulking agent characteristics • Moderate labor and energy requirements	• Large footprint required • Highly affected to climate impacts • High operating and maintenance cost on blowers • Large volume of bulking agent required • Large volumes of air required to treat odor
Windrow	• Rapid drying with elevated temperatures • Drier finished compost product • Ability of high volume material • Good product stabilization • Low capital investment • Proven technology on small scale • Adaptable to changes in bulking agent characteristics • Minimally dependent on mechanical equipment • Low energy requirement	• Large footprint required • High operational costs • Turning equipment required • Highly affected to climate changes • High potential odor problem during turning • Large volume of bulking agent required • Difficult to capture air for treatment
In-vessel	• Small footprint required • Not labor intensive • Good process control • Applicable to climate conditions • Good odor control • Potential for heat recovery • Continuous process option • Small volume of process air required • Moderate energy requirement	• High capital cost • Lack of operating data for large systems • Careful management required • Highly mechanical and electrical equipments required • Potential for incomplete stabilization • Less flexibility in operation mode • Sensitive to changes in bulking agents

Sources: Chiumenti *et al*. 2005; Sylvia *et al*. 2005; Tchobanoglous *et al*. 2003; U.S. EPA 1999

As shown in Table 3-2, all three composting systems are viable proven technologies, and generate beneficial by-products. To determine the most viable process option, the following factors should generally be considered as selection criteria:

- Equipment and labor availability
- Siting and area considerations
  - Wind direction
  - Topography
  - Ground water protection
  - Area requirement
  - Existing area
- Compost utilization
- Climate
- Capital, operating, and maintenance costs, and
- Control of public health and nuisance factors

In conclusion, composting is a proven organic waste management and stabilization process, and successful operation of a compost facility includes three basic components – efficient materials handling, effective odor control, and a successful compost dispersion/marketing program. Depending upon the goals and certain waste streams, the design, installation, and management of a potential composting system requires careful planning and consideration of the limitations of systems. Good process control and system management are particularly required to provide that the composting processing system continues to ensure the objectives of the user(s), and that the quality of the surrounding environment is not negatively impacted upon.

3.2 ANAEROBIC DIGESTION

Anaerobic digestion (AD) is an effective biological process to convert the organic fraction of waste streams to methane (CH_4) and carbon dioxide (CO_2) rich biogas suitable for energy production in the absence of oxygen. AD is a common waste-to-energy technology for various types of combined and separated organic waste streams.

The technology has been used for over 100 years and thousands of AD systems have been installed in Europe and the U.S. since the 1970s. Since the 1990s, better designed, more successful projects have come on line in the U.S. Several environmental conditions such as moisture content, temperature, and pH levels in an enclosed reactor can successfully be controlled to maximize biogas generation and waste reduction. The biogas by-product generated during the digestion process can be used on-site as a supplement/replacement for natural gas, to generate electricity, or within a combined heat and power system to provide both heat and electricity. An additional option is to upgrade the biogas to natural gas pipeline quality and then inject into the natural gas network or even use as a vehicle fuel.

Recent developments in AD technology have shown that varied waste streams range from food, yard, and commercial wastes to agricultural residues can be processed. In many countries, animal waste/manure and crop residues that are derived from food production, are the largest source of wastes. The best use of these wastes is land application for nutrient recycling to crops, but lack of adequate land for optimum nutrient use and odor control has necessitated the need for suitable treatment and disposal methods. Conversion of these waste streams into a renewable energy resource has been the focus of intensive progress for more than two decades. Where costs are high for waste disposal, and the effluent has economic value, AD technology and biogas production can reduce overall operating costs.

The general pathways of AD technology, as shown in Figure 3-2, have a multi-phase process. The first phase of the process involves the conversion of biodegradable organic materials in the waste stream to soluble compounds and volatile fatty acids. The soluble matter is then converted to biogas in the second step. Depending on the waste stream and the system design, biogas typically consists of up to 70% methane; the remaining composition is primarily carbon dioxide, trace gases such as hydrogen sulfide, nitrogen, and water. Although all AD processes follow the same pathway, design and operation of this technology varies widely, depending on the process controlling factors and site-specific conditions.

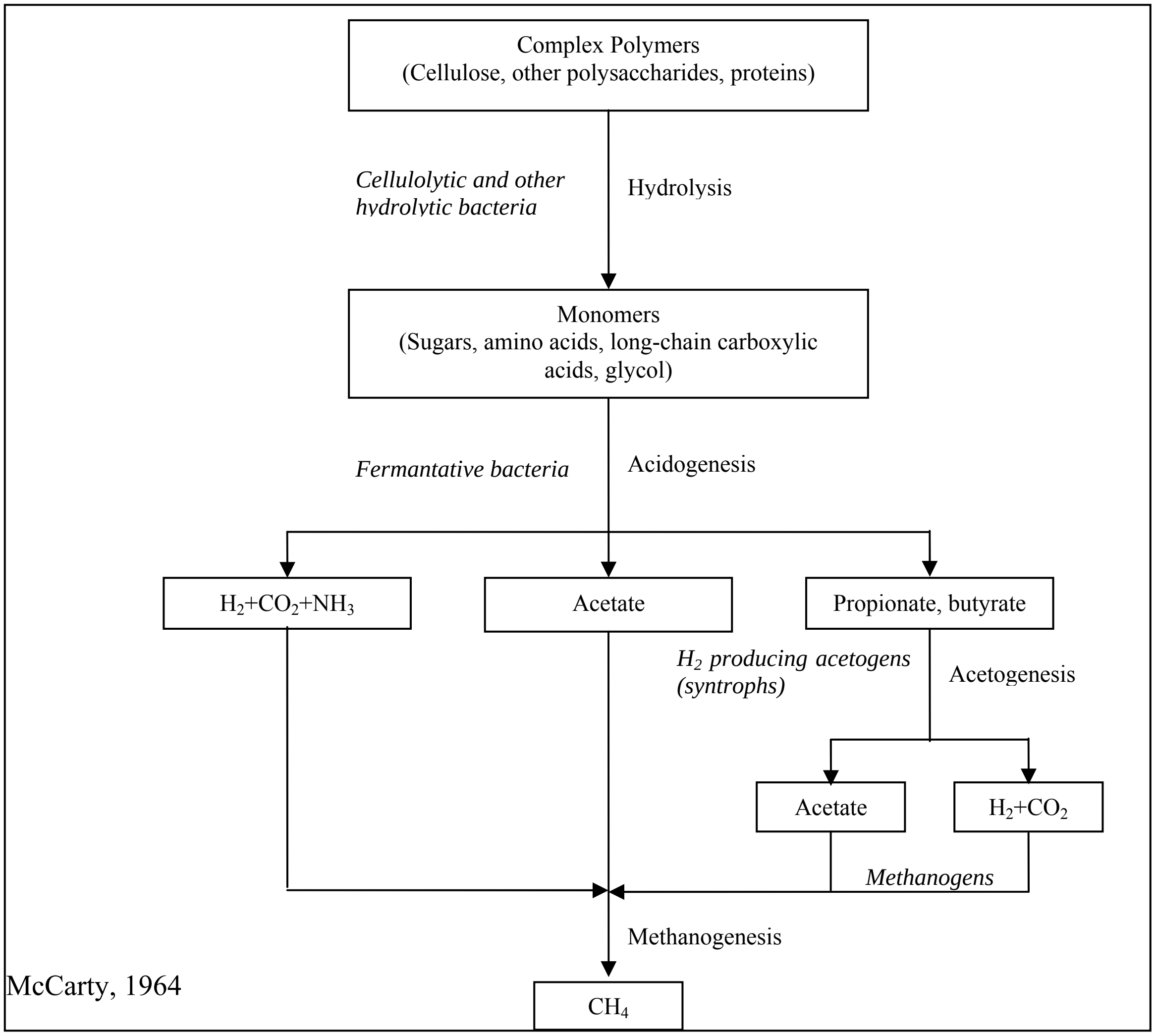

Figure 3-2
General Pathways of Anaerobic Digestion

As shown in Table 3-3, the efficiency and rate of AD technology is generally controlled by the factors to maximize the process performance:

Table 3-3
Controlling Factors of Anaerobic Digestion Performance

Physical Factors	Chemical Factors
• Temperature	• pH
• Hydraulic Retention Time	• Alkalinity
• Solids Retention Time	• Volatile Acids
• Solids Loading Rate	• Nutrients
• Mixing	• Trace Elements
• Solids Concentration	• Toxic Compounds
• Biomass Type	
• Volatile Solids Loading	

Among these factors, solids concentration, quantified by total solids (TS) content, is one of the key factors that distinguishes different types of organic waste streams, and controls the design of the AD system. Based on TS content in the waste stream, AD can be designed using dry AD, and wet AD technologies.

Dry AD technologies, typically applied with solids content greater than 20 percent, require limited amounts of water to be added in the waste stream. Reducing the volume of water results in use of a smaller reactor vessel (less cost) and lower operating cost. The other benefits of dry AD technology include:

- Lower process energy demand for heating the reactor vessel since feed volumes are lower,
- Reduced post-digestion residue volumes to manage, and
- Increased process stability and reliability

Wet AD technologies, which typically process with less than 20 percent total solids, are more commonly used in waste management practices. By diluting the wastes with water, the concentration of constituents such as ammonia and volatile organic acids can be lowered to below inhibitory levels. Dilution of wastes also allow for a well-mixed process in the digesters and greater reduction efficiency with higher biogas production potential. The other benefits of wet AD include:

- Extraction of inert solids such as sand periodically
- Obtain better homogenization of feedstock

The key design features of AD technology include:

- Digestion stages (Single versus two stage)
- Operating temperature (Mesophilic versus thermophilic process)
- Digester type (Vertical versus horizontal)
- Process flow (Continuous versus batch or semi-continuous), and
- Agitation (Agitator versus gas injection or recirculation)

3.2.1 Anaerobic Digestion Process of Organic Waste Stream

AD of organic waste streams is largely implemented as a wet or dry treatment process conducted in enclosed tanks to maintain the anaerobic conditions (absence of free oxygen) in combination with capture of the methane gas. There are numerous steps to the process that are common to all anaerobic digestion technologies. Combining these steps yields the following seven basic process steps:

- Waste receiving
- Mechanical pre-treatment and conditioning of wastes to homogenize, optimize moisture levels, and pre-heat
- Anaerobic digestion
- Biogas and heat utilization
- Solids dewatering
- Processing of digested residue (depending on product requirements)
- Wastewater and exhaust air/odor treatment

For waste receiving, techniques are employed to minimize odors and optimize the storage of waste stream to be processed. Separation of food, yard, and other organic materials is used as a feedstock for anaerobic digestion, and heat and/or electricity is generated from biogas.

To prepare materials for digestion, a mechanical pre-treatment step is utilized. The mechanical pre-treatment required for anaerobic digestion provides the advantage of removal of virtually all contaminants, inorganics, and other non-degradable material, resulting in a high quality feedstock for digestion. Mechanical treatment and conditioning may include screening and sorting of the waste stream to separate out litter and other nondigestable materials; metals or other inappropriate waste that would impact the quality of digestion and/or the finished product or damage the processing equipment.

In the anaerobic digestion process, various populations of microorganisms work closely together to transform degradable organic matter under anaerobic conditions into biogas and water. Biogas consists primarily of carbon dioxide and methane. The contents of anaerobic digesters must be heated to the desired process temperature while keeping the contents mixed. The degradable organic matter or volatile solids are significantly reduced in mass. Pathogenic organisms that may be contained in the waste stream are significantly reduced as a function of retention time and temperature. The typical maximum reduction in volatile solids is about 60 percent. The poor efficiency in degrading lignin-containing feedstocks and the potential inhibitory effects of impurities may limit anaerobic digestion resulting in an accumulation of organic acids and ultimate failure of the process.

Biogas and heat generated during the digestion process would be collected, treated or cleaned of impurities (such as hydrogen sulfide and carbon dioxide), as necessary, and its energy content utilized through:

- Injection into the natural gas grid
- Cogeneration of electricity and heat using gas or dual-fueled internal combustion engines or microturbines
- Heat generation in gas boilers for residential or commercial use, or
- Additional compression or liquefaction to fuel internal combustion engines of various fleet vehicles (compressed natural gas vehicles)

Dewatering of the digested residue would be accomplished using various types of dewatering equipment and/or water flocculent aided applications. Part of this filtrate water would then be returned to the process cycle to minimize water consumption, while the balance would be treated and discharged (with a permit) to the sanitary sewer as wastewater.

In terms of residual solids management, the product of anaerobic digestion attains the quality of raw compost that is still biologically active, and cannot be stored. Without additional processing, the application of these solids is limited. Also, wastes comprised of wood are not suitable for anaerobic digestion, as it is difficult to break down lignin, a main component of wood, under anaerobic conditions. Therefore, in order to generate a stable solid product of high stability, the digested residue needs to be treated in a subsequent process.

Odorous fumes and process air generated in the waste receiving area, the mechanical treatment and conditioning stage, the dewatering unit, solids storage, and processing digested residue operations would be collected and cleaned using scrubbers and/or biofilters for odor control at the facility and to minimize the impact to surrounding communities. Otherwise, the anaerobic digestion and biogas cleanup process minimizes odors that are otherwise discharged into the atmosphere. Shown in Figure 3-3 is an example process schematic of a wet and single-stage anaerobic digestion.

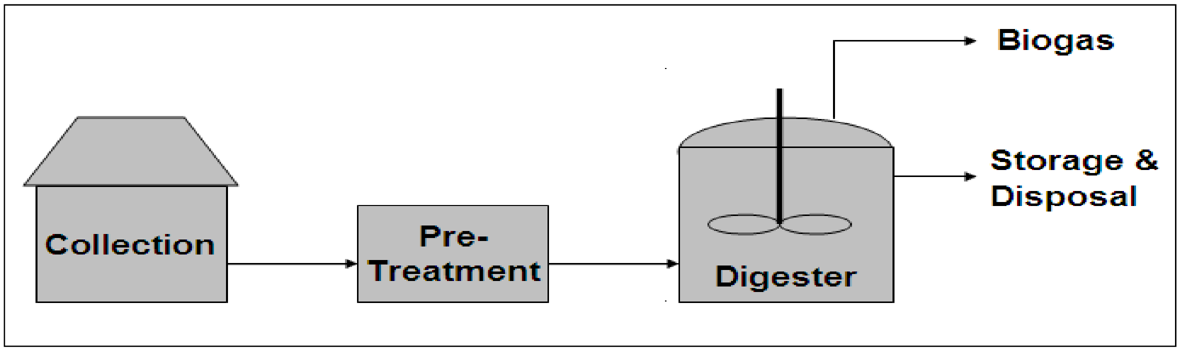

Figure 3-3
Wet Single Stage Anaerobic Digestion Process

Depending on the technical and economic viability of such an organic waste management project, the following variables can significantly change costs and should be considered in the selection and optimization of a viable and sustainable AD system:

- Land price
- The range and purity of organic waste stream collected
- Recovery rates of organic waste streams
- Landfill tipping fees
- Waste stream hauling costs
- Markets for biogas and digested product
- Operating and maintenance cost
- Government and/or state regulations for environmental considerations
- Tax credits, and
- Renewable energy portfolio benefits

3.2.2 Integrated Anaerobic Digestion and Composting System

Integrating AD and a composting system can derive the benefits of both of these processes while minimizing their limitations. While anaerobic digestion of suitable feed stocks can provide energy to generate electricity or heat, the difficult-to-digest components in the waste stream can be composted to produce a sterilized end product in the form of compost. The other benefits of integrated anaerobic digestion and composting system include a lower carbon footprint and reduced transfer and transportation costs due to a reduction in the finished product quantity from the composting operations. The potential revenue from sale of the biogas as compared to the composted product would need to be further evaluated.

3.3 GASIFICATION

The last alternative technology for converting organic waste streams to energy is gasification. Through this process, the waste stream is thermally converted to a mixture of carbon monoxide (CO) and hydrogen (H_2), known as synthesis gas (syngas). This syngas can be further processed to produce fertilizers, electricity, or liquid fuels.

Gasification process occurs under reducing conditions with sub-stoichiometric amounts of oxygen. A carbon-based feedstock is converted to syngas in the presence of steam and oxygen within a vessel known as a gasifier. Reactions occur within the gasifier at extreme conditions with temperatures in excess of 2,000 ^{o}F and pressures between 400 pounds per square inch gauge (psig) and 1,000 psig. The chemistry involved in gasification is complex and includes the following reactions (Stiegel et al 2006).

$$C + 1/2\ O_2 \leftrightarrow CO \qquad \Delta H_f = -111.4\ MJ/kmol$$

$$C + O_2 \leftrightarrow CO_2 \qquad \Delta H_f = -393.4\ MJ/kmol$$

$$C + CO_2 \leftrightarrow 2\ CO \qquad \Delta H_f = 170.7\ MJ/kmol$$

$$C + H_2O \leftrightarrow CO + H_2 \qquad \Delta H_f = 130.5\ MJ/kmol$$

$$C + 2\ H_2 \leftrightarrow CH_4 \qquad \Delta H_f = -74.7\ MJ/kmol$$

$$CO + H_2O \leftrightarrow H_2 + CO_2 \qquad \Delta H_f = -40.2\ MJ/kmol$$

As shown in Figure 3-4, there are three typical gasifier configurations currently in use in the industry (Phillips 2006):

- Moving Bed or Downdraft
- Entrained Flow, and
- Fluidized Bed

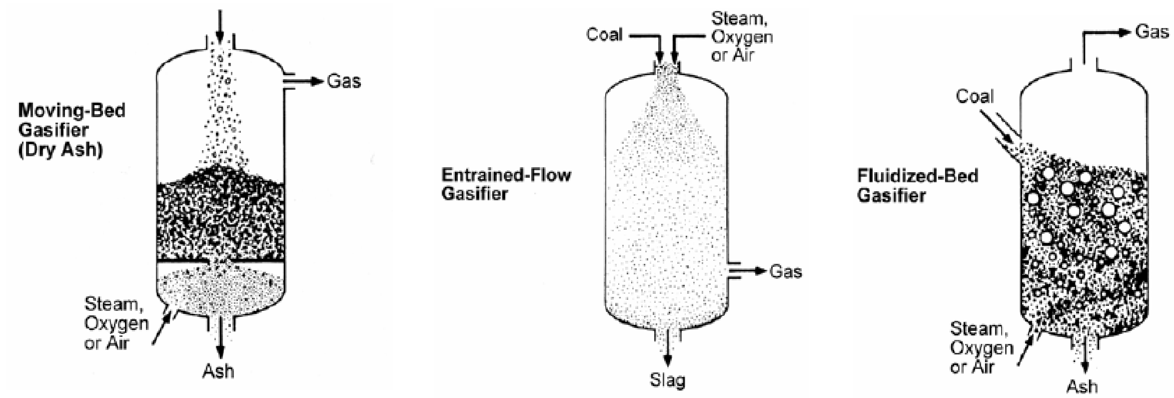

Figure 3-4
Types of Gasification Process

In a moving bed or downdraft gasifier, large particles of fuel are fed into the top of the vessel and move downward, contacting steam and oxygen/air counter-currently. As the fuel moves down the reactor, it is gasified. Due to the counter-current configuration, the heat of reaction from the gasification reactions is able to preheat the fuel before it enters the gasification zone. As a result, the temperature of the syngas exiting the gasifier is significantly lower than the temperature required for complete conversion of the fuel.

In an entrained flow gasifier; finely ground fuel is injected co-currently with the oxygen and steam. The fuel heats rapidly and reacts with the oxygen/air. The residence time in this gasifier is significantly shorter than that of a moving bed gasifier. Because of this short residence time, entrained flow gasifiers must be operated at high temperature to ensure high conversion of carbon. To achieve this high temperature, most entrained flow gasifiers utilize pure oxygen rather than air.

A fluidized bed gasifier is a well-stirred reactor where a consistent mixture of fresh fuel particles is continuously mixed with older partially, and fully, gasified fuel particles. The flow of steam and oxygen/air into the gasifier controls the mixing and must not be so high as to entrain the fresh fuel out of the bed. As the fuel particles are gasified, however, they will become small enough that they will be entrained out. The mixing in the vessel also serves to maintain a uniform temperature throughout the bed.

The benefits of gasification process include the following:

- Greater efficiency
- Easier handling
- Achieving 75% of weight and 90% of volume reduction of total waste stream
- Limited plant area required
- Less back-end pollution control required
- Wider array of potential products from the process (i.e. electricity, liquid fuels, substitute natural gas)

3.4 MUNICIPAL AND COMMERCIAL ORGANIC WASTE PROCESSING FACILITIES IN THE REGION

As presented above, composting, AD, and gasification technologies are viable for use by Boulder County. Within the region, Tetra Tech identified five commercial and municipal organic waste processing facilities that are utilizing composting technologies. Within Boulder County, Western Disposal operates a commercial compost facility at the Butte Mill Road facility. Western Disposal compost operations are subsidized by Boulder County and the City of Boulder. A-1 Organics is a large commercial organic waste management company that has locations throughout northern Colorado. A-1 Organics produces mulch and compost from organic waste for resale to the public. A-1 Organics primarily utilizes windrow composting technology. Similarly, Hageman Earth Cycle, Inc. located near Fort Collins, Colorado is a commercial organic waste processor that uses windrow composting technology. The City of Cheyenne Wyoming and Francis E. Warren Air Force Base both operate municipal organic waste processing facilities that utilize windrow composting technology. Francis E. Warren Air Force Base has previously utilized enclosed static pile composting (Ag-Bag) composting technology, but that practice ceased over 3 years ago in favor of standard windrow composting.

Currently, there are no known AD or gasification organic waste processing facilities in operation along Colorado's Front Range; however, two New Energy Economic Development grants from the Governor's Energy Office through the state Clean Energy Funds were specifically tailored to AD and gasification technology development. These grants were awarded in January 2009 to evaluate AD and gasification technology feasibility in Greeley, Colorado and develop a wood waste processing and gasification project in Chaffee County. Boulder County should monitor the developments of these projects and consider the outcomes in future decision making processes. Boulder County could also submit a grant application for a new Energy Economic Development grant to further evaluate AD and gasification feasibility within the county.

3.5 GREENHOUSE GAS EMISSION IMPACTS

In addition to evaluating the technical and economic feasibility of various organic waste management technologies, Boulder County requested a preliminary evaluation of potential GHG emission impacts of alternative organic waste management technologies identified in this report. The primary GHG emissions associated with the organic waste management are related to transportation and material processing. This evaluation presents GHG considerations and potential emissions to support future decision making efforts. Specific, detailed GHG emissions will need to be determined once siting, technology, specific throughput volumes and other key decisions are made.

3.5.1 Transportation Related Greenhouse Gas Emissions

GHG emissions related to transportation are primarily indirect carbon dioxide emissions associated with collection and transporting organics to a centralized processing facility. There are various figures available in literature that provides planning level estimates for GHG emissions. The U.S. EPA estimates that 363,000 British Thermal Units (btu) in the form of diesel fuel is required to collect and transport one ton of organics to a central compost facility (U.S. EPA 2006). Using the EPA's assumed 0.02 metric tons of carbon equivalents (MTCE) per million Btu of diesel fuel, it is estimated that 0.0073 MTCE of indirect emissions are generated per ton of organic material collected and transported for centralized processing (EPA 2006). There are existing centralized organic waste management facilities located within the county and the alternatives presented in this evaluation will still require collection and transportation of the material to centralized processing areas. Utilizing the EPA methodology, it estimated that there will be little change to GHG emissions associated with collection and transportation of each ton of organic waste.

3.5.2 Composting Greenhouse Gas Emissions

According to EPA research and analysis, composting technologies can generate GHG emissions in the form of methane (CH_4) from small pockets of anaerobic decomposition of organic material that may form; however the EPA "concluded from the available information that CH_4 generation from centralized compost piles is essentially zero" (U.S. EPA 2006, p. 50). While GHG emissions from composting processes are considered negligible, GHG emissions associated with turning and manipulating compost piles during processing can be quantified using EPA published data. The EPA estimates that 221,000 Btu in the form of diesel fuel is required to turn and manipulate one ton of organics being composted (EPA 2006). Using the EPA's assumed 0.02 MTCE per million Btu of diesel fuel, it is estimated that 0.0044 MTCE of indirect carbon dioxide emissions per ton of organic material processed (EPA 2006). Although there are GHG emissions generated during the compost process, the overall net emissions reduction including soil carbon sequestration, processing, and transportation is 0.05 MTCE per ton of organic material processed (EPA 2006).

3.5.3 Anaerobic Digestion Greenhouse Gas Emissions

GHG emissions related to anaerobic digestion technologies are primarily associated with CH_4 production during the digestion process. Although CH_4 is generated in large quantities, the CH_4 is captured and used to fuel energy recovery, resulting in a potential GHG emission reduction or sink (U.S. EPA 2006). It is estimated that 0.03 MTCE of GHG emissions per ton of organic material processed can be reduced using anaerobic digestion technologies.

3.5.4 Gasification Greenhouse Gas Emissions

GHG emissions related to gasification technologies are primarily associated with CO_2 and N_2O production during the combustion process. N_2O has a global warming potential of 310, meaning it is 310 times as potent of a GHG as CO_2. It is estimated that the net GHG emission reduction for gasification including transportation to the facility, combustion emissions, and avoided utility emissions is 0.05 MTCE per ton of organic material processed. There are avoided utility emissions because the energy recovered in the waste-to-energy process displaces electricity that would otherwise be provided by an electric utility power plant.

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4.0 TECHNOLOGY BENEFITS AND IMPACTS EVALUATION

Based upon the above discussion of alternative waste management technology options, Tetra Tech has evaluated the potential environmental benefits and impacts of viable technologies for use by Boulder County. When properly designed and applied, these technologies not only minimize the organic waste streams in the county, but also enable sustainable energy production and recovery of valuable by-products. Therefore, each technology introduces several benefits along with the potential environmental concerns that should be addressed depending on what is most valued by Boulder County.

The environmental impacts that should be considered include numerous planning and execution procedures, regulations, and requirements associated with the alternative technologies. The evaluation in this report uses information developed in other technical feasibility studies along with publicly available literature data from other resources, currents regulations, and standards. Table 4-1 shows the benefits and environmental impacts for composting, AD, and gasification of organic waste.

In conclusion, translating some of these benefits into net present value and determining a return on the investment generally require a significant effort. This effort is warranted to better understand the aggregate environmental benefits of a viable waste management system.

Table 4-1
Environmental Benefits and Impacts of Viable Waste Management Technologies

Viable Technology	Benefits	Environmental Impacts
Composting	• Reduction in landfill organic waste streams • Reduction in greenhouse gas emissions and pathogens • Marketable product (compost)	• Required operating permit • Air pollution permit due to generation of gas and odor • Compost classification • Wastewater permit (with AD application)
Anaerobic Digestion	• Reduction in landfill organic waste streams • Reduction in greenhouse gas emissions and pathogens • Renewable energy generation (heat, power, fertilizer, and compost) • Eliminating or minimizing odor problem • Generating RECs and carbon offset credits • Improved water quality • Enhanced air quality	• Requires operating permit • Air pollution permit to install and operate due to gas emissions • Wastewater permit • Nutrient management • Modifications for the off-site discharge of the AD effluent stream • Federal and/or state regulations for the digested sludge
Gasification	• Reduction in landfill waste streams • Reduction in greenhouse gas emissions • Renewable energy generation (fertilizer, power, and liquid fuels) • Odor minimization • Lower quantities of air pollutants • Non-hazardous and readily marketable by-products • No need for water usage	• Requires operating permit • Air pollution permit standards for nitrous oxide, sulfur dioxide, and carbon dioxide • Federal and/or state regulations for waste products • There may be local operation and interconnection permits for tie-in to electric utility lines

5.0 ECONOMIC EVALUATION

As Boulder County decision makers consider future organic waste management alternatives, the economic costs and benefits must be considered. This section discusses potential cost and revenue impacts for the viable organic waste technologies presented in this report. This preliminary economic analysis is based on several assumptions, previous project experience, literature, and other sources. This preliminary economic analysis is meant to provide Boulder County decision makers with rough order of magnitude level costs and benefits, as well as other factors that would impact future organic waste management practices.

It is estimated that 79,300 tons of food, wood and yard waste is generated each year within Boulder County. Based on national recovery rates published by the EPA, if these waste streams are recovered at the national average, 24,007 tons of organic material would be available for processing. Currently, Boulder County and municipal organic waste collection programs process approximately 25,880 tons per year of food, wood and yard waste which is slightly above the national recovery rate. This economic analysis assumes that Boulder County could capture and process the existing 25,880 tons of organic waste being managed in the county. It is also assumed that an additional 25 percent, or 6,470 tons, capacity should be planned to account for increased program participation, population growth, and other factors that would increase the amount of material being collected. These assumptions yield an overall planning capacity of 32,350 tons of organic waste to be processed per year.

5.1 CAPITAL AND OPERATING COSTS OF ORGANIC WASTE MANAGEMENT TECHNOLOGIES

This section provides rough order-of-magnitude cost estimates for each technology presented in this report. These cost estimates are generalized from other projects conducted by Tetra Tech, available literature and other sources. These estimates are approximate for determining the potential feasibility of viable systems and to provide a basis for more detailed evaluations. A detailed system design and cost estimate would need to be developed after receipt of additional siting details, technical analysis (e.g., detailed waste quantity analysis, and laboratory and potential pilot scale studies), and the designed processing system or system(s).

A composting system is considered a viable option suitable for the processing of organic waste streams. The capital costs for a new composting process are estimated to be between $300 and $500 per ton for in-vessel composting while the expected capital cost of an aerated static pile facility is between $85 and $100 per ton. The anticipated capital costs for windrow composting systems have been reported to be $40 to $60 per ton per year (Composting Council of Canada 2010) and it is estimated that an enclosed static pile (Ag-Bag) system will cost between $50 and $75 per ton in capital cost (City of Palo Alto 2008). Typical Operations and Maintenance (O&M) costs for in-vessel systems range from $100 to $280 per ton and are highly dependent on system configuration and equipment choice (U.S. EPA 2000). Operating costs for aerated static pile systems range from $10 to $70 per ton while operating costs for enclosed static pile (Ag-Bag) system are expected to range from $50 to $75 per ton (P2 Pays 2000 and Delaware Solid Waste Authority). Operating costs for windrow composting have been reported to range between $15.00 and $26.00 per ton (BioCycle 2005, City of Palo Alto 2008, and City of Modesto 2008). Table 5-1 summarizes the range of capital and operational costs for each of the composting systems discussed in this report.

Table 5-1
Specific Investment Costs for Composting Facilities

Composting System	Capital Costs ($/Ton of Capacity/year)	Operational Cost ($/Ton of Capacity/year)
Windrow	$40 - $60	$15 - $26
Enclosed Windrow	$100 - $150	$20 - $40
Aerated Static Pile	$75 - $125	$10 - $70
Enclosed Static Pile (Ag-Bag)	$50 - $75	$40 - $70
In-vessel	$300 - $500	$100 - $280

Anaerobic Digestion process generally requires facilities for receiving material, preparing, digestion, digester gas management and energy recovery, as well as residual digestate and excess liquid management. The capital costs for a source separated waste stream of a typical AD process are estimated to range from $245 to $635 per ton of yearly design capacity. These costs would be 5-10% higher for a mixed waste facility that requires sorting machinery and greater floor space (New York City Department of Sanitation 2002). Table 5-2 indicates both capital and operating costs for a typical system operating with an AD process (Tetra Tech 2003):

Table 5-2
Specific Investment Costs for Anaerobic Digestion Plants

Plant Scale	Capital Costs ($/Ton of Capacity/year)	Operational Cost ($/Ton of Capacity/year)
	Range	Range
Small	$408 - $862	$82 - $123
Medium	$295 - $567	$68 - $113
Large	$225 – $499	$45 - $91

Notes: Small scale plants with a throughput of 4,500 to 5,500 tons per year
Medium scale size plants with a throughput of 9,000 to 13,500 tons per year
Large scale plants with a throughput of 18,000 to 27,000 tons per year

Gasification technology continues to gain interest as a means to recover energy from waste streams. Compared to the established process of thermal oxidation, gasification process is considered innovative as gasification technologies are in varying stages of pilot and full scale demonstration and have limited operating cases in the U.S. Cost-effectiveness and performance depend highly on material dryness, and may require other feed materials (i.e., wood waste, green waste) in order to produce sufficient power. The capital costs for a typical gasification process are estimated to range from $490 to $720 per ton of biomass per year, or $1,100 to $1,600 per ton of biomass per kWe generation. Typical O&M costs range from 15% to 20% of total capital cost of the plant (Gasification Technologies Council 2010).

Table 5-3 presents a summary of the potential capital and annual operating costs for Boulder County given the above rough order of magnitude cost ranges and the assumed 32,350 tons per year planning capacity of the system.

Table 5-3
Potential Capital and Annual Operating Costs

Technology	Capital Cost	Annual Operating Cost
Composting		
Windrow	$1,290,000 - $1,941,000	$485,000 - $841,000
Enclosed Windrow	$3,235,000 - $4,853,000	$647,000 - $1,294,000
Aerated Static Pile	$2,426,000 - $4,044,000	$323,500 - $2,265,000
Enclosed Static Pile (Ag-Bag)	$1,618,000 - $2,426,000	$1,294,000 - $2,265,000
In-vessel	$9,705,000 - $16,175,000	$3,235,000 - $9,058,000
Anaerobic Digestion	$7,277,000 - $16,138,000	$1,467,100 - $2,934,200
Gasification	$15,852,000 - $23,292,000	$2,378,000 - $3,494,000

5.2 POTENTIAL REVENUE EVALUTION

Organic waste management and processing can generate revenue and economic benefit in a variety of ways, primarily by charging tipping fees for depositing organic material at the processing facility and by selling the end products once the waste is processed. Potential revenue from tipping fees is applicable to all technologies evaluated in this report; however, potential revenue from the sale of end products will vary dramatically based on the technology. The following paragraphs discuss potential revenue for tipping fees and for the end products of the technologies presented in this report.

5.2.1 Tipping Fees

Tipping fees are charged by landfills and other solid waste management facilities for accepting material brought to the facility for processing. Currently, county and municipal organic waste drop-off facilities vary in the application of tipping fees. At some organic waste drop-off facilities, such as the Butte Mill Road facility, a tipping fee is charged to certain patrons, primarily contractors and non-residents, but other patrons can utilize the facility at no cost. The tipping fee at the Butte Mill Road facility is 50 percent of the landfill disposal tipping fee which provides economic incentive for generators to use the processing facility instead of opting for landfill disposal. Other municipal drop-off locations have similar restrictions on contractors and non-residents, and most do not charge authorized users for the use of the drop-off facility.

Potentially charging a tipping fee must be carefully considered and the fee itself must be set as to not dissuade generators from using the facility. The trash disposal fees near Boulder vary, but two landfills near Denver charge $22.00 per ton. Using the current pricing structure for the Butte Mill Road facility in which organic waste can be deposited for 50 percent of the solid waste disposal fee, the tipping fee for organic waste can be assumed to be $11.00 per ton. It should be noted that some organic waste facilities charge up to $19.50 per ton. If the $11.00 per ton tipping fee was charged to all users and the estimated 32,350 tons of organic material is brought to the facility, Boulder County could expect to obtain an estimated $355,850 per year in tipping fees.

5.2.2 Potential Revenue from Compost Technology End Products

The primary end product of the compost technologies presented in this report is mulch and high quality compost that can be sold to residents and contractors for landscape activities. Based on the estimated 32,350 tons of materials being processed and assuming 0.5 tons of compost are generated for each ton of organic material processed, 16,175 tons of finished mulch and compost will be generated (Waste Age

1997). Currently, municipal and commercial compost operations charge various fees for end products based on the type, quantity, and quality of the end product. For mulch, prices range from \$12.00 to \$33.00 per cubic yard. Finished compost prices range from \$22.00 to \$30.00 per cubic yard. Using a price point of \$22.00 per cubic yard and assuming 463 pounds per cubic yard for the finished product, it is possible that Boulder County could receive over \$1,500,000 in annual revenue from the sale of these end products.

5.2.3 Potential Revenue from Anaerobic Digestion End Products

Anaerobic Digestion technology is expected to greatly reduce the organic waste loading to landfills while generating a sustainable renewable energy resource. An AD bioreactor treating 32,350 wet tons of organic waste will produce an estimated 88,315,500 cubic feet of digester gas per year, which can potentially generate 5.434 Megawatts per year of electricity based on engine generators operating at 35 percent electrical efficiency. Electrical service rates vary based on customer and usage type, time of use, and other factors. For this evaluation, the per kilowatt hour rate is assumed to range from \$0.07 to \$0.10 per kilo watt hour (kWh). Using this range, the on-site electricity generation equates to approximately \$380,380 to \$543,400 of savings in electricity costs per year. Because the AD process would generate sustainable renewable energy, it is likely that the AD process will also benefit from Renewable Energy Credits (REC). The value of RECs varies based on how the renewable energy is generated, but range from \$0.05 - \$0.07 per kWh in the area. Using this range, Boulder County could get \$271,700 to \$380,380 per year by selling RECs. Further, due to GHG emission reductions of approximately 968 tons carbon, it is possible that some economic benefit in the form of carbon offset credits can be realized from this process.

Once processing is complete, the AD digester effluent would be separated into liquid and solid phases, both of which are have potential residual value. The liquid effluent contains a high level of soluble nutrients that can be used for irrigation and/or agricultural applications within Boulder County. The solids portion of the effluent can be composted to produce high quality compost that can be marketed as discussed above. Due to the volume reductions associated with the AD processing, the volume of compost is expected to be less than 5,000 tons. Based on this volume and the revenue discussion presented above, Boulder County could potentially receive \$475,000 in revenue from the sale of this compost.

5.2.4 Potential Revenue from Gasification End Products

Gasification technologies produce synthesis gas (syngas), which is a mixture of gases, predominantly carbon monoxide and hydrogen. Syngas can be burned in a combustion turbine to generate electricity which can be sold to the local utility. Waste heat can be recovered to generate additional electricity or for heating. In typical gasification of mixed MSW, there would be residual slag that could be sold, but, in the case of combusting organics, there is no residual for sale. The U.S. EPA estimates that organic wastes generate 261 kWh per ton of organic waste (U.S. EPA 2006). Using the estimated 32,350 tons of organic material collected, Boulder County could generate 8,443,350 kWh. Electrical service rates vary based on customer and usage type, time of use, and other factors. For this evaluation, the per kilowatt hour rate is assumed to range from $0.07 to $0.10 per kWh. Using this range, the on-site electricity generation equates to approximately $591,035 to $844,335 of savings in electricity costs per year.

5.2.5 Summary of Potential Revenue

Table 5-4 summarizes the potential revenue for each of the alternative organic waste management technologies presented in this report.

Table 5-4
Potential Revenue

Technology	Potential Annual Revenue
Composting	
Tipping Fee	$355,850
Compost Sales	$1,500,000
Total	$1,855,850
Anaerobic Digestion	
Tipping Fee	$355,850
Energy Sales	$380,380 - $543,400
Compost Sales	$475,000
Renewable Energy Credits	$271,700 - $380,380
Total	$1,482,930 - $1,754,630
Gasification	
Tipping Fee	$355,850
Energy Sales	$591,035 - $844,335
Total	$946,885 - $1,200,185

5.2.6 Summary of Economic Analysis

Table 5-5 summarizes the rough order of magnitude potential costs and revenues for each of the alternative organic waste management technologies presented in this report.

Table 5-5
Summary of Economic Analysis

Technology	Capital Cost	Annual Operating Cost	Revenue
Composting			
Windrow	$1,290,000 - $1,941,000	$485,000 - $841,000	$1,855,850
Enclosed Windrow	$3,235,000 - $4,853,000	$647,000 - $1,294,000	$1,855,850
Aerated Static Pile	$2,426,000 - $4,044,000	$323,500 - $2,265,000	$1,855,850
Enclosed Static Pile(Ag-Bag)	$1,618,000 - $2,426,000	$1,294,000 - $2,265,000	$1,855,850
In-vessel	$9,705,000 - $16,175,000	$3,235,000 - $9,058,000	$1,855,850
Anaerobic Digestion	$7,277,000 - $16,138,000	$1,467,100 - $2,934,200	$1,482,930 - $1,754,630
Gasification	$15,852,000 - $23,292,000	$2,378,000 - $3,494,000	$946,885 - $1,200,185

5.3 ECONOMIC ANALYSIS OF SMALL ORGANIC WASTE MANAGEMENT FACILITY

The economic analysis presented thus far in Section 5.0 assumes that a new alternative organic waste management facility in Boulder County would receive, manage, process, and obtain all the economic benefit associated with the end products generated. Based on these assumptions, an estimated 32,350 tons of organic waste would be processed at the facility. It is highly likely that a new facility managed by Boulder County could process this much material based on the following factors:

- Based on EPA generation rates and current recovery rates of food, wood and yard waste, it is estimated that more than 50,000 tons of organic waste could be recovered in Boulder County
- Currently, many organic waste generators in Boulder County deliver organic waste to a commercial composting facility located in Plattesville CO. It can be assumed that if Boulder County develops a new organic waste management facility within the county, these generators would choose to use the closest facility.
- Boulder County and the City of Boulder currently subsidize an organic waste management facility at Butte Mill Road. If Boulder County develops a new organic waste management facility, it can be assumed that those subsidies would cease and prices at the current commercial facility would increase to recover the lost revenue. If this occurs, Boulder County could develop a tipping/pricing structure to be competitive with commercial facilities and incentivize waste generators to use the new facility.

As described above, it is possible that a new alternative organic waste management facility in Boulder County could collect and process 32,350 tons per year. Based on this estimated 32,350 tons of organic waste available, Western Disposal currently processes approximately 15,000 tons per year while other municipal and commercial programs within the county process an additional 10,000 tons per year. Based on current collection volumes, existing commercial and municipal organic waste diversion alternatives in the county, and the significant investment costs associated with a new facility, a smaller alternative waste management facility could be considered by Boulder County decision makers to reduce costs and risks associated with creating a new facility. The following paragraphs discuss the potential economic costs and benefits of a 10,000 ton alternative organic waste management facility in Boulder County.

5.3.1 Summary of Potential Capital and Operating Costs for Small Organic Waste Management Facility

Table 5-6 summarizes the potential capital and operating costs for a 10,000 ton per year alternative organic waste management facility in Boulder County. It should be noted that the capital costs for composting systems are relatively similar for large or small systems because initial capital costs are associated with equipment purchases and site preparation which can be scaled based on expected throughput at the facility. As shown in Table 5-2, AD facilities are more directly related to the size and scale of the facility being installed and Table 5-6 shows potential capital and operating costs associated with a small plant. Gasification technology costs are directly related to the expected throughput of the facility.

Table 5-6
Potential Capital and Annual Operating Costs of 10,000 Ton per Year Facility

Technology	Capital Cost	Annual Operating Cost
Composting		
Windrow	\$400,000 - \$600,000	\$150,000 - \$260,000
Enclosed Windrow	\$1,000,000 - \$1,500,000	\$200,000 - \$400,000
Aerated Static Pile	\$750,000 - \$1,250,000	\$100,000 - \$700,000
Enclosed Static Pile (Ag-Bag)	\$500,000 - \$750,000	\$500,000 - \$750,000
In-vessel	\$3,000,000 - \$5,000,000	\$1,000,000 - \$2,800,000
Anaerobic Digestion	\$2,950,000 - \$5,670,000	\$680,000 - \$1,130,000
Gasification	\$4,900,000 - \$7,200,000	\$735,000 - \$1,080,000

5.3.2 Summary of Potential Revenue for Small Organic Waste Management Facility

It is estimated that the per ton tipping fee and sale of end products will remain the same for a large or small facility, so the volume of material processed will control the amount of revenue received. Section 5.2 discusses the potential revenue calculations utilized for this economic evaluation. Table 5-4 summarizes the potential revenue for a 10,000 ton per year alternative organic waste management facility in Boulder County.

Table 5-7
Potential Revenue of 10,000 Ton per Year Facility

Technology	Potential Annual Revenue
Composting	
Tipping Fee	$110,000
Compost Sales	$475,000
Total	$585,000
Anaerobic Digestion	
Tipping Fee	$110,000
Energy Sales	$117,583 - $167,970
Compost Sales	$150,000
Renewable Energy Credits	$83,985 - $117,579
Total	$461,568 - $545,549
Gasification	
Tipping Fee	$110,000
Energy Sales	$182,700 - $261,000
Total	$292,700 - $371,000

5.3.3 Summary of Economic Analysis for Small Organic Waste Management Facility

Table 5-5 summarizes the rough order of magnitude potential costs and revenues for a 10,000 ton per year alternative organic waste management facility in Boulder County.

Table 5-8
Summary of Economic Analysis of 10,000 Ton per Year Facility

Technology	Capital Cost	Annual Operating Cost	Revenue
Composting			
Windrow	$400,000 - $600,000	$150,000 - $260,000	$585,000
Enclosed Windrow	$1,000,000 - $1,500,000	$200,000 - $400,000	$585,000
Aerated Static Pile	$750,000 - $1,250,000	$100,000 - $700,000	$585,000
Enclosed Static Pile(Ag-Bag)	$500,000 - $750,000	$500,000 - $750,000	$585,000
In-vessel	$3,000,000 - $5,000,000	$1,000,000 - $2,800,000	$585,000
Anaerobic Digestion	$2,950,000 - $5,670,000	$680,000 - $1,130,000	$461,568 - $545,549
Gasification	$4,900,000 - $7,200,000	$735,000 - $1,080,000	$292,700 - $371,000

6.0 CONCLUSION AND RECOMMENDATIONS

The overall objective of this report is to assist Boulder County with identifying potential organic waste management opportunities, reduce environmental footprint and waste streams, potentially diversify the County's energy portfolio, and help to educate Boulder County by providing alternative management approaches as well as the merit of these technologies for generation of potential renewable energy application and use.

Although composting technology is not a renewable energy technology, it offers relatively lower initial capital costs, waste minimization, and a useable/saleable end-product. The other key advantages of composting are that the technology has a self-contained footprint, ability to be located in close proximity to highly sensitive receptors (the general public), and is a low risk/robust technology. Additionally, it is possible to develop a central composting facility for use by Boulder County and municipalities within the county. It is also possible to develop decentralized compost facilities, similar to current practices, for approximately the same costs and benefits presented in this evaluation. Equipment and labor availability, climate change, and control of public health and nuisance factors are possibly considered the disadvantages of this technology.

Anaerobic digestion and gasification processes offer renewable energy production with a compact and self-contained footprint. Advantages that can be realized by both of these technologies include decreasing both Boulder County's electrical and thermal costs due to renewable energy potential, minimizing wastes, and offsetting disposal requirements/costs. Both gasification and anaerobic digestion technologies are capital intensive as compared to composting. Gasification technologies typically have higher capital costs, operation and maintenance costs, and process risks as compared to the anaerobic digestion, however; the return on investment is possibly higher than other options evaluated due to its high process efficiency. Due to the high capital costs of anaerobic digestion and gasification technologies as well as significant infrastructure costs associated with these technologies, multiple, decentralized processing facilities within the county is not a feasible alternative for these technologies.

Based on the information and discussion from this feasibility evaluation, Tetra Tech believes that alternative organic waste management technologies are likely to be technically and economically feasible options for Boulder County. It is recommended that the following actions be accomplished by Boulder County decision makers to support future organic waste management operations.

- This evaluation assumed that Boulder County would centrally manage a future alternative organic waste processing facility. Currently, several municipalities within the County have established organic waste management programs that could be impacted by this operational change. It is recommended that Boulder County explore partnering with these municipalities to pool resources to support a proposed alternative organic waste management facility and maximize the volume of material being processed. If a collaborative agreement is not reached, the economic analysis presented in this report should be updated, using the same methodology, to determine the cost and benefit impacts of reduced processing volume.

- This evaluation focused on technical and economic feasibility of alternative organic waste management practices. If, based on this evaluation, Boulder County decision makers decide to move forward, potential locations should be identified and evaluated. Additionally, detailed cost estimates and site evaluation would need to be accomplished based on site specific factors.

- Investigate federal, state, and local incentives (grants, tax incentives, etc) that could support funding of the alternative waste management processes Boulder County decision makers would like to pursue based on this preliminary evaluation.

- Perform a sensitivity analysis to assess which variable factors are likely to have a significant impact, on the overall success and economic outcome for Boulder County.

7.0 REFERENCES

A-1 Organics (2010)
2010 A-1 Organics company website. Available at http://www.a1organics.com/. May

Assmuth, T.W. and Strandberg T
1993 Groundwater contamination at Finnish landfills. *Water, Air and Soil Pollution,* 69(1/2): 179-199

BioMass Magazine
2009 Colorado biomass projects receive NEED grants. Available at http://www.biomassmagazine.com/article.jsp?article_id=2368. Accessed June 2010.

BioCycle
2005 Latest Trends in Yard Trimming Composting. Volume 46, No. 9, page 22. September

Borden, R.C. and Yanoschak T.M
1990 Ground and surface water quality impacts of North Carolina sanitary landfills. *Water Resources Bulletin,* 26(2): 269-277

City of Modesto
2008 Council Agenda Report: Tip Fees for Pre-Ground Materials at Modesto Composting. January 28.

City of Palo Alto
2008 The City of Palo Alto Compost Facility Feasibility Report. April.

Chiumenti A., Chiumenti R., Diaz L.F., Savage G.M., Eggerth L.L. and Goldstein N
2005 Modern Composting Technologies. Journal of Composting & Organics Recycling.

Composting Council of Canada
2010 Composting Processing Technologies website. Available at http://www.compost.org/pdf/compost_proc_tech_eng.pdf . May

Delaware Solid Waste Authority
2004 Analysis of the Impact of a Yard Waste Ban on Landfill Quantities and Household Costs. Available at: http://www.dnrec.state.de.us/DNREC2000/Divisions/AWM/YardWaste/PDF/, Sept.

Gasification Technologies Council
2010 Gasification Technologies Council website/ Available at http://www.gasification.org/. May.

Harkness, G.E., Reed, C.C., Voss, C.J. and Kunihiro, C.I
1994 Composting in the Magic Kingdom. *Water Environment and Technology*, 6(8): 64-67.

International Council for Local Environmental Initiatives (ICLEI)
2008 Local Government Operations Protocol for the quantification and reporting of greenhouse gas emissions inventories, Version 1.0. September. http://www.iclei.org/fileadmin/user_upload/documents/Global/Progams/CCP/Standards/LGOP_USA_2008.pdf.

McCarty, P.L.
1964 Anaerobic Waste Treatment Fundamentals: Chemistry and Microbiology, Public Works.

NatureWorks
2005 Nature Works website. Available at http://plusonewater.ca/media/compost_facilities.pdf. May.

New York City Department of Sanitation
2002 New York City Commercial Waste Management Study Preliminary Report.

Philips, J.
2006 The Gas Turbine Handbook, Section 1.2.1 – Different Types of Gasifiers and Their Integration with Gas Turbines, National Energy Technology Laboratory.

Recycled Organics Unit
2001 Greenhouse Gas Emissions from Composting Facilities (Report for Central Coast Waste Board, Recycled Organics Unit). Available at www.recycledorganics.com.

RIS International Ltd.
2005 Feasibility of Generating Green Power through Anaerobic Digestion of Garden Refuse from the Sacramento Area (Final Report).

Russel, G.M. and A.L. Higer
1988 Assessment of groundwater contamination near Lantana landfill, southeast Florida. *Ground Water,* 26(2): 156-164.

Steelman, T. and Devona B
2009 Community Responses to Wildland Fire Threats in Colorado Case Studies Boulder County. Available at http://www.ncsu.edu/project/wildfire/Colorado/boulder/boulder.html.

Stiegel, G.J., Massood R. and Howard G.M.
2006 The Gas Turbine Handbook, Section 1.2 – Integrated Gasification Combined Cycle, National Energy Technology Laboratory.

Sylvia D.M., Fuhrmann J.J., Hartel P.G. and Zuberer D.A.
2005 Principles and Applications of Soil Microbiology. Pearson Prentice Hall, New Jersey.

Tchobanoglous G., Burton F.L. and Stensel H.D.
2003 Wastewater Engineering Treatment and Reuse. Metcalf & Eddy Inc., New York.

Tetra Tech Inc.
2003 Anaerobic Digestion of Source Separated Food Study. Technical Memorandum No. 1 - Digestion Technologies Assessment, February, 2003.

Tetra Tech Inc.
2010 Organic Waste Generation and Management Survey Report for Boulder County, Colorado.

U.S. EPA
1997 Greenhouse Gas Emissions from Municipal Waste Management. Report prepared for the Office of Policy, Planning and Evaluation, U.S. Environmental Protection Agency.

U.S. EPA
1999 Biosolids Technology Fact Sheet, Use of Composting for Biosolids Management, U.S. Environmental Protection Agency.

U.S. EPA
2000 Biosolids Technology Fact Sheet, In-Vessel Composting of Biosolids. U.S. Environmetnal Protection Agency.

U.S. EPA
2003 Municipal Solid Waste in The United States: 2001 Facts and Figures.

U.S. EPA
2006 Solid Waste Management and Greenhouse Gases A Life-Cycle Assessment of Emission and Sinks.

U.S. EPA
2009 Municipal Solid Waste Generation, Recycling, and Disposal in the United States Detailed Table and Figures for 2008.

Waste Age
1997 Meeting Diversion Goals: Compost Countdown. June 1. Available at http://wasteage.com/mag/waste_meeting_diversion_goals/.

Waste Enquiry
2000 Alternative Waste Management Technologies and Practices Inquiry. Sydney, Australia.