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Omni-Processor Landscaping Project

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OMNI-PROCESSOR LANDSCAPING PROJECT

FOR THE BILL & MELINDA GATES FOUNDATION

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EXECUTIVE SUMMARY

According to the World Health Organization (WHO), there are one billion people in the world who do not have access to water and approximately 2.4 billion who do not have access to any type of improved sanitation facilities. About two million people die every year due to diarrheal diseases, most of them being children less than five years of age. The Bill & Melinda Gates Foundation established a global development program area, *Water, Sanitation & Hygiene*, which focuses on sanitation that works for the poor in developing countries. A primary theme of this initiative is the vision of an Omni-Processor than can convert excreta (i.e., latrine waste) into beneficial products such as energy and soil nutrients with the potential to develop local business and revenue. The Omni-Processor should be capable of the following: produce a safe product that has value, support a sustainable business model, be adaptable to changing conditions, be community based, and use local skills and materials.

Over 50 technologies or processes were identified that could be used to treat excreta and produce energy and nutrient products. To be successful in developing countries, there are basic criteria that the Omni-Processor must meet including: simple and adaptable technology that is "free standing" without the need for extensive infrastructure such as electricity, water, and sewers. Twelve technologies met these basic criteria and are listed in Table 3-1. While all 12 of these technologies are applicable for developing countries, they do not all hold equal promise to meet the Omni-Processor objectives.

The most promising technologies for the Omni-Processor vision are not single technologies, but technologies and processes which can be coupled to convert excreta into recoverable energy and soil amendment products. Technologies based on bioconversion provide the greatest chance of success compared to thermal conversion processes which are generally too complex for application on small scale in developing countries.

The highest reuse potential from human excreta lies in using its stabilized organics (humus), nitrogen, phosphorus, and trace elements to improve the soil profile and help achieve sustainable agricultural practices. Bioconversion using anaerobic digestion is the key starting process to realize this vision. Anaerobic digestion can biologically stabilize the raw organics and produces a valuable biogas in the process. The biogas can be used as an energy source wherever heat is needed, such as cooking and space heating. More advanced uses of the gas are possible including combined heat and power (CHP) generation (i.e., Stirling engines and other CHP alternatives) to recover both heat and electrical energy.

Anaerobic digestion sets the stage for a number of reuse possibilities that are simply not practical with raw excreta. Liquid digested sludge can be directly applied to agricultural land to recover the nitrogen, phosphorus, trace elements, and organic humus values within the material. The combination of anaerobic digestion and proper land and crop management can achieve a low risk of pathogen transport. Liquid digested sludge can be stored in storage basins or lagoons to achieve additional pathogen destruction, provide a buffer to meet cropping cycles, and further reduce the odor characteristic of the product. If partially dried, the digested waste can be amended with other materials and composted to produce a soil amendment. A compost product can be stored to match crop cycles, but may find other uses and business potentials such as potting soil. Vermicomposting (using earthworms) is also possible to further improve the attractiveness of the final product.

To be successful, particularly in the developing world, a sanitation-based business needs an ongoing relationship with a customer that, if well done, will benefit the customer (clean toilet, recovered energy or product) and the service provider (money). There are several factors important to creating a sustainable business model. Entrepreneurs must see people as customers who want a service at a reasonable price. Assistance must be provided with any technology and this is particularly so for people living in places difficult to access with extreme climate conditions. There are opportunities for innovation here, but the innovation may not be in finding a novel process, but in adapting established technologies in ways to fit developing world communities. Finally, management guidance will be needed, from operation and maintenance of the technology to sale and distribution of the by-products. The success of these technologies, either alone or coupled, will depend on how well the process is managed.

A key recommendation of this report is to focus on bioconversion processes, starting with anaerobic digestion, to improve sustainable agricultural practices as the best approach to realizing the Omni-Processor vision. Several follow-up studies are recommended (see Section 5.4) to guide development of an implementation strategy. Significant researchers and technology developers are identified for anaerobic digestion, co-generation of energy, and soil amendment (see Appendix B).

CHAPTER 1.0

INTRODUCTION

1.1 Background

According to the World Health Organization (WHO), approximately 2.4 billion people do not have access to any type of improved sanitation facility. About two million people die every year due to diarrheal diseases, most of them being children less than five years of age. The most affected are the populations in developing countries, living in extreme conditions of poverty. The WHO attributes this situation to the following conditions:

- Lack of priority given to sanitation
- Lack of financial resources
- Lack of sustainability of sanitation services
- Poor hygiene behaviors

Providing access to facilities for a sanitary disposal of excreta, and introducing sound hygiene behaviors, are of critical importance to reduce the burden of disease caused by these factors.

The Bill & Melinda Gates Foundation desires to help all people lead healthy, productive lives. In developing countries, the Foundation's Global Development Program focuses on improving people's health and giving them the chance to lift themselves out of hunger and extreme poverty. Their programs concentrate on areas with the potential for high-impact – sustainable solutions that can reach millions of people by working closely to support innovative approaches and expand existing ones so they reach the people who need them most. The newest Global Development Program area – *Water, Sanitation & Hygiene* – focuses on sanitation that works for the poor.

1.2 Omni-Processor Vision

The Foundation's Omni-Processor project objective is to identify and develop technologies for urban sanitation and excreta management in developing countries. It is to be a small-footprint system to safely process human excreta, and possibly also urban organic waste, into products that can be re-used. It should also create a business that could generate revenue. The system would serve 1,000-5,000 people and be able to be implemented at the neighborhood level. Products generated could be anything that can be re-used locally, such as heat energy, products usable for cooking, soil amendment, mineral ash, as well as recovered water. The Omni-Processor should be free-standing: independent of electricity, water, or sewer lines.

The Omni-Processor should convert various waste types from urban-residential living, foremost being human excreta (i.e., latrine waste), but also food waste, into environmentally preferred forms. Because developing communities often do not have conveyance (i.e., sewers and other conduits), and often inhabitants resort to open defecation, the Omni-Processor must not rely on sewers or waterborne sanitation. Also, many developing countries do not have adequate power and water available for running equipment at a treatment site. The treatment technologies must be operational without relying on power and water.

Another key aspect of the Omni-Processor would be to support a business model based on an ability to generate revenues and minimize capital and operational costs. Sustainability and scalability require the revenues of the products generated to cover at least the operation and maintenance of the units, so that the processing units can be run as a business or cover the cost of running a municipal service. Figure 1-1 illustrates the Omni-Processor vision.

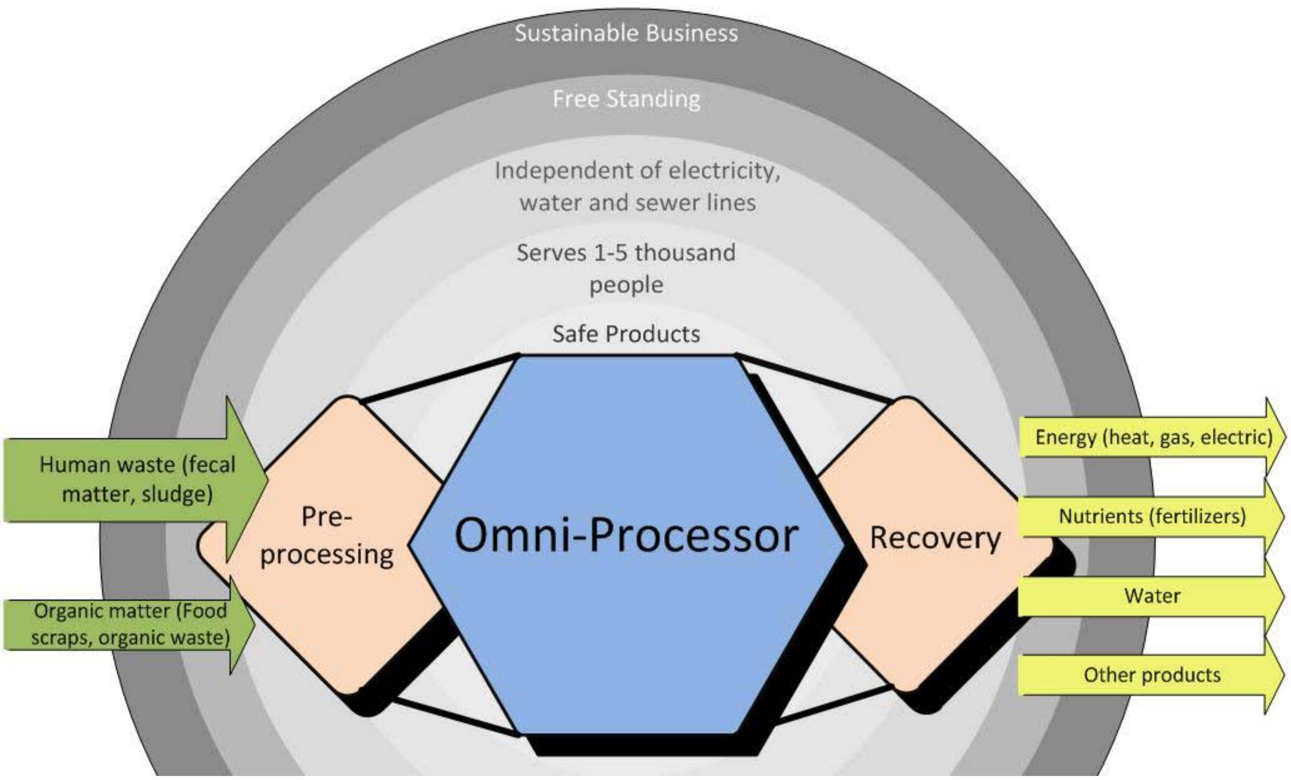


Figure 1-1. Omni-Processor Vision.

1.3 Project Approach

The Bill & Melinda Gates Foundation engaged the Water Environment Research Foundation (WERF), an independent not-for-profit scientific research organization that funds and manages water quality research, to evaluate the universe of technologies, both established and novel, to identify those technologies which can, either standing alone or coupled into a system, meet the objectives of the Omni-Processor vision.

Through a creative brainstorming process, experts with extensive professional experience developed a comprehensive list of technologies and processes that meet the goals of the Foundation's Omni-Processor vision. The team evaluated these technologies across a set of criteria which reflect the Omni-Processor vision. The outcome of the brainstorming and evaluation was reviewed and augmented by five expert advisors to vet the soundness of this evaluation, the resulting recommendation of technologies and processes, and the list of key players for further implementation.

The technology identification and evaluation process is summarized in the following sections of this report:

- Overview of resource recovery opportunities for excreta treatment processes.
- Listing of process technologies with potential to fulfill the Omni-Processor vision.
- Summary of the criteria and WERF's phased evaluation approach used to relatively compare and screen technologies for further consideration.
- Recommendations for Omni-Processor technologies that should be considered and further developed including practical implementation given site, economic, and community conditions.

CHAPTER 2.0

UNIVERSE OF TECHNOLOGIES AND PROCESSES

2.1 Overview

Access to sound sanitation is a cornerstone to improving the lives of people in developing countries. In addition, economic benefits can be attained by using technologies that can convert human waste (excreta) into renewable resources, such as biogas and soil amendment**.** Seizing opportunities to recover these resources may provide a better chance for a *sustainable* future.

There are two categories of readily recoverable resources in excreta and food wastes – energy and nutrients. This chapter identifies the universe of the potential technologies and processes that could used for energy and nutrient recovery, while successfully managing excreta co-mingled with residential food wastes. These technologies are selected from a global perspective with the Omni-Processor vision in mind. Most technologies are proven; some are in the developmental stage.

2.2 Energy Recovery

The embedded energy in organic wastes, including excreta and food waste, is significant. This is the energy content stored in the various organic chemicals in the wastes. When not diluted with water in sewered infrastructure, the excreta is more concentrated and contain more energy per unit. Residue separated from wastewater contains approximately 8,000 British thermal units per pound (Btu/lb) on a dry weight basis, which is similar to the energy content of low-grade coal. The potential for energy recovery is a function of the composition of the waste and the type of treatment technology employed. There are two primary pathways for energy recovery: *bioconversion* and *thermal conversion*. An overview of various processes, their corresponding energy products, and residual products for these two pathways are shown in Table 2-1.

Table 2-1 summarizes the recoverable energy products produced by the conversion process technologies under consideration for the Omni-Processor. This table provides a basis for the universe of technologies evaluated under this study, specific for energy recovery.

	Treatment Process	Energy Product	Energy Use	Residual Product	End Uses
Bio Conversion	Anaerobic Digestion	Biogas Fuel Gas	Process Heat Power Generation Vehicle Use or Natural Gas Replacement	Moist Solids	Soil Amendment
Bio Conversion	Composting	NA	NA	Dried product	Soil Amendment
Thermal Conversion	Incineration Co-Combustion	Heat	Process Heat Power Generation	Ash	Landfill
Thermal Conversion	Thermal Drying – Gasification	Syngas Fuel Gas	Process Heat Power Generation Vehicle Use or Natural Gas Replacement	Ash	Landfill
Thermal Conversion	Pyrolysis – Thermal Drying	Bio-oil Dried Fuel	Process Heat Alternative Fuel		
Thermal Conversion	Thermal Drying (alone or in combination)	Dried Fuel	Alternative Fuel	Dried Solids	Soil Amendment Land Reclamation

Figure 2-1. Conversion Pathways, Processes, and Products.
Adapted from NACWA, 2010, *Renewing our Commitment to Renewable Energy: Banking on Biosolids Energy Recovery*.

2.3 Nutrient Recovery

Nitrogen (N) and phosphorus (P) are critical elements both in agricultural systems (demand) and contained in excreta and food waste (resource). There is reason to look into recovering the nutrients from these sources in a safe manner. In addition, excreta and food waste contain a significant amount of organic material. This organic material is a very valuable resource in emerging countries. The organic material helps preserve and build up the existing soil. It also helps sandy soil to hold water and breaks up clay soil so it easily drains, both of which increase crop yields.

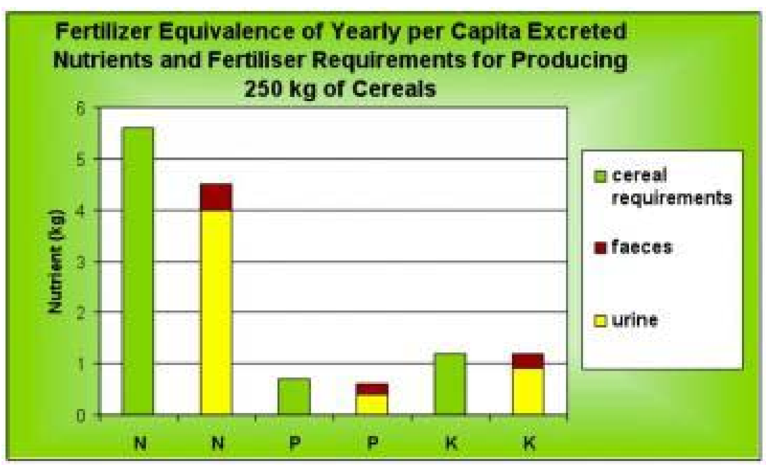


Figure 2-2. Fertilizer Equivalence of Yearly per Capita Excreted Nutrients and Fertilizer Requirements for Producing 250 kg of Cereals.
Source: WERNER (2004)

It has been estimated that humans alone excrete nitrogen in their wastes at a rate between 4.5 and 7.5 kg/person/yr. In 2008, the Food and Agriculture Organization of the United Nations projected that the world demand for nitrogen fertilizer would be 1.39 million metric tons/year. With six billion people, human excrement could potentially supply 19-32% of the global nitrogen fertilizer demand. By comparison, chemical fixation of one kilogram of ammonia in the Haber-Bosch process requires 55 millijoules of energy and the total chemical production of ammonia may account for 1-2% of annual global greenhouse gas emissions. Material and energy costs as well as environmental impacts can be offset by the recovery of organic nitrogen and ammonia from human excreta.

Wastewater and excreta, together with animal manure and organic household waste, have the potential to provide all of the nutrient requirements with minimal or no application of synthetic, chemical-based fertilizer. These resources can serve as important sources for soil amendments, as they deliver all relevant nutrients and water needed for plant growth, as well as organic matter. Indeed, agriculture and achieving food security is historically strongly linked with the idea of reusing liquid and solid waste from households. Throughout centuries, human and animal excreta played a crucial role in maintaining soil fertility and providing essential plant nutrients for food production. If agriculture is to be sustainable, these concepts should be revived.

Phosphorus is also a global concern, as readily available phosphorus is being depleted at an unsustainable rate. While the exact supply of available phosphorus can be debated, current reserves are projected to be depleted in this century – with some estimating that the planet will be in short supply by 2050. In addition, nearly 90% of the world's estimated phosphorus reserves found in just five countries: Morocco, China, South Africa, Jordan, and the U.S. Reducing use of synthetic chemical fertilizers through more sustainable methods, such as the beneficial use of properly treated solids from human and food waste, is an area that becomes more compelling in light of these global trends. These considerations are the basis for the universe of technologies evaluated under this study for nutrient recovery.

2.4 Assessment of the Universe of Technologies and Processes

The research team conducted an extensive literature review and discussed applicable technologies during numerous conference calls with the team participants and advisors. A comprehensive list of processes was developed (Universe of Technologies and Processes). The research team, using a two-phased evaluation approach, screened and collated technologies that best fit the Omni-Processor vision and criteria. Results of this evaluation are described in the next section. Brief descriptions of each technology and process are provided in Appendix A, with more details on why each specific process or technology was either eliminated from further consideration or retained for consideration as part of the Omni-Processor.

The list of technologies and processes, provided in Table 2-1, was reviewed and refined by the experts.

Table 2-1. Universe of Technologies and Processes.

Omni – Processor Vision			
Bio Conversion	Thermal Conversion	Combined Heat and Power	Post Processing and Nutrient Recovery
Aerobic Digestion	Sludge to Liquid Fuel	Burn Gas for Heat	Thermal Drying
Anaerobic Digestion	Sludge to Syngas	Internal Combustion Engines	Air Drying
Single Stage	Steam/CO_2 Reforming	Fuel Cells	Solar Drying
Multiple Stage	Gasification	Turbines (steam)	Lime Stabilization
Lagooning	Pyrolysis	Turbines (combustion)	Soil Amendment
Plug-flow	Sludge to Heat	Stirling Engines	N Recovery (ARP)
Thermophilic	Incineration	Burn Gas for Heat	P Recovery
In-situ Digestion in Landfill	Vitrification		
Composting	Plasma		
Wetlands Treatment	Super-critical Oxidation		
Vermicomposting	Low-tech Combustion		

CHAPTER 3.0

EVALUATION OF ALTERNATIVES

3.1 Evaluation Criteria and Process

The research team evaluated the list of processes to determine which technologies and processes would be appropriate to manage excreta and food waste to recover valuable resources in developing countries. The evaluation was performed in two phases. The objective of the first phase was to evaluate the universe of global technologies, processes and equipment against a set of criteria that reflected key attributes of the Omni-Processor vision. Those technologies and processes suitable for a developing country and meeting the Phase 1 criteria, were included in the Phase 2 evaluation. The rankings were vetted by the experts and refined during discussion.

3.1.1 Phase 1 Criteria

The positive-rated technologies and processes meeting the Phase 1 criteria selected technologies or processes that can be "free standing" and independent of the need for electricity, water, and sewers. In addition, the criteria included an evaluation of the complexity of each technology. A simple technology appropriate for a community in the developing world, as defined for this project, does not require extensive training or education to understand and operate, and has low capital and operating costs. The universe of technologies and processes were rated against the Phase 1 criteria and highly rated ones were identified for further evaluation.

3.1.2 Phase 2 Criteria

The technologies and process meeting the Phase 1 criteria were compared to the Phase 2 criteria, which are aggregated categories of attributes taken from the Omni-Processor vision statement. The highest ranked technologies (most positive against the criteria) from the Phase 1 evaluation were then rated against the Phase 2 criteria to identify the technologies and processes, used alone or in combination, which hold the most promise for the Omni-Processor vision. There are six criteria for Phase 2 which include:

- **Produces "Safe" Products** – This process significantly reduces pathogens in the excreta, has limited direct handling requirements, limited odor potential, a small carbon footprint, and for energy recovery technologies, does not emit significant air pollutants. Acknowledging that the level of management provided to any process or operation of a technology affects the 'quality' of the product, processes with variable product safety were given a neutral rating. Processes with unsafe products, i.e., attracts vectors or emits significant air pollutants, were rated as a negative.
- **Produces Valuable Products** – This process produces products that are a source of energy and/or nutrients. This may include gas, dried material for fuel, and/or wet and dry material for N, P, or potassium (K) for use as a soil amendment. Products with variable or marginal value were rated neutral. Those with no value were rated negative.

- **Adaptability** – A process is rated positive if it can accommodate waste streams other than excreta, such as food waste and green waste, and can be located in diverse climates that are wet, dry, hot, cold, or at high elevations.
- **Small and Community Based –** The processes are rated positive if they are both appropriate for a small-scale applications, have a small footprint, and have few impacts on the neighborhood, such as odor or traffic. Processes that meet one but not all elements noted above are rated neutral. Those not meeting at least two of the three elements are rated negative.
- **Sustainable Business Model** – The processes that may support a business model (i.e., produce products or services that produce revenue, have the potential for net positive gain, and are affordable, with low capital and operating costs) are rated positive. Those less likely to fit the business model are rated neutral. Those unlikely to fit the business model are rated negative.
- **Success with Local Skills and Materials –** The processes which do not require skilled labor or importation of parts and services from developed countries are rated positive. Also, the construction should be with local materials to the greatest extent possible. Those less likely to function with local skills or be built with local materials are rated neutral. Those unlikely to match with local skills and materials are rated negative.

3.2 Evaluation of Technologies

3.2.1 Phase 1 – Technologies and Processes

The processes and technologies were rated against the criteria in Phase 1 (independent of the need for electricity, water, and sewers and simple). Those processes or technologies that ranked generally positive against the Phase 1 criteria, are highlighted. The results of the evaluation are in Table 3-1.

3.2.2 Phase 2 – Technologies and Processes

The processes and technologies meeting the Phase I criteria were further rated against the Phase 2 criteria. Those meeting the Omni-Processor vision and thus recommended for consideration, are highlighted in Table 3-2 and described in detail in Section 4.0.

Table 3-1. Evaluation of Technologies – Phase I.

Universe of Technologies	Omni Vision Criteria Phase I No Electricity Required	No Water Required	No Sewers Required	Simple Technology
Bio Conversion				
Aerobic Digestion	–	0	0	+
Anaerobic Digestion				
Single Stage	+	+	+	+
Multiple Stage	0	+	+	–
Lagooning/ Storage	+	–	+	+
Plug-flow (not mixed)	0	+	+	–
Thermophilic	0	+	+	–
In-situ Digestion in Landfill	+	+	+	0
Composting	+	+	+	0
Wetlands Treatment	+	–	+	+
Vermicomposting	+	+	+	0
Thermal Conversion				
Sludge to Liquid Fuel	–	–	0	–
Sludge to Syngas				
Steam/CO_2 Reforming	0	0	+	–
Gasification	–	–	0	–
Pyrolysis	–	–	0	–
Sludge to Heat				
Incineration	0	0	+	–
Vitrification	–	0	0	–
Plasma	–	0	0	–
Super-critical Oxidation	–	–	0	–
Low-tech Combustion	0	0	+	+
Combined Heat and Power Recovery				
Burn Gas for Heat	+	+	+	+
Internal Combustion Engines	0	+	+	0
Fuel Cells	+	+	+	–
Turbines (steam)	–	–	0	–
Turbines (combustion)	–	–	0	–
Stirling Engines	+	+	+	0
Processing and Nutrient Recovery				
Thermal Drying	0	0	0	–
Air Drying (open/covered)	+	+	+	+
Solar Drying	+	+	+	+
Lime Stabilization	0	+	+	0
Soil Amendment	+	+	+	+
N Recovery from Sludge	–	–	–	–
P Recovery from Sludge	–	0	–	–

Key: + designates desirable attributes relative to criteria (i.e., + under no electricity required means electric power is not a significant need); 0 designates neutral or mixed attributes; and – designates negative attributes relative to criteria (i.e., under no electricity it means electric power is a major requirement).

Table 3-2. Evaluation of Technologies – Phase 2.

Phase 2 Technologies	Omni Vision Criteria Provides: Produces Safe Products	Produces Valuable Products	Adaptability	Small and Community-Based	Sustainable Business Model	Fits with Local Skills/Materials
Bio Conversion						
Anaerobic Digestion – Single Stage	+	+	+	+	+	+
In-situ Digestion in Landfill	0	0	+	–	+	+
Lagooning/Storage	+	+	0	–	+	+
Composting	+	+	+	0	+	+
Wetlands Treatment	0	0	–	–	–	+
Vermi Composting	+	+	0	0	+	+
Combined Heat and Power Recovery						
Burn Gas for Heat	0	+	+	+	+	+
Internal Combustion Engines	0	+	0	+	+	–
Fuel Cells	+	+	–	+	+	–
Stirling Engines	0	+	+	+	+	0
Processing and Nutrient Recovery						
Air Drying (open/covered)	0	+	0	–	+	+
Solar Drying	0	+	0	0	+	+
Lime Stabilization	+	0	0	+	0	+
Soil Amendment	+	+	+	+	+	+

Notes:
Acceptable technologies for the Omni-Processor are highlighted in blue. Selection based on technologies all positive except for one negative or two neutral criteria.

CHAPTER 4.0

RECOMMENDATIONS

4.1 Introduction

As the universe of possible technologies and processes was rated against the criteria important for the Omni-Processor, several technologies emerged as successful candidates. Some of these process or technology candidates are best coupled with others to achieve the Omni-Processor vision. The possible sequences of coupling processes and technologies likely to work successfully together are discussed in Section 5.0. This section provides a detailed discussion of the recommended processes and technologies, particularly from the perspective of use in developing countries. The references used in this section are listed in the Reference Section by process.

4.2 Technologies and Processes Not Well Suited to the Omni-Processor Vision

Some technologies and processes not meeting the Omni-Processor vision still have value in developing world communities to provide safe management of excreta in certain situations. These were not recommended for the Omni-Processor vision, often because of their large land foot print requirements and their unsuitability for placement in neighborhood settings. Nevertheless, the processes summarized in Table 4-1 have potential to be successfully applied in specific situations in developing countries. The detailed description of these second-tier technologies is in Appendix A.

Table 4-1. Summary of Attributes of Technologies and Processes Not Well Suited to the Omni-Vision.

Technology/Process	Attributes			
	Low-Tech, Simple Operations	Demonstrate to Meet Business Model	Works Well Only in Some Climates	Works Well When Ample Land is Available
In-situ Digestion in Landfill	Needs gas collection system and liners	Yes – can collect biogas	Yes	Yes – better suited for larger communities over 5,000
Lagooning/Storage	Yes	Yes – produces duck weed and algae for fish food	Yes -- in warm, moist regions	Yes – but need less in hot climates
Wetlands Treatment	New approach for latrine waste	Yes – possible to grow for flower markets	Needs wetlands	Yes
Air Drying (open/covered)	Yes	Yes – dried fuel or soil amendment	Yes – hot, dry	yes
Solar Drying	Yes	Yes – dried fuel or soil amendment	Yes – hot, dry	yes
Lime Stabilization	Needs local source of lime	N/A	N/A	N/A

Although the processes listed above are not recommended for the Omni-Processor, they may still be viable under certain specific applications. Solar drying came very close to becoming a recommended process, and may be successfully coupled with other processes, such as anaerobic digestion, to dry the solids remaining after digestion to produce a soil amendment. Internal combustion engines are established and well understood. They are not recommended here because they require skilled maintenance and gas pretreatment, but they would be appropriate in certain applications to recover heat and electric energy from biogas. Fuel cells are a new technology with great potential. That being said, they are very complicated to successfully operate on biogas, even by skilled staff. Other organizations and agencies worldwide are investing significant research into fuel cells. Innovation and the progress of new developments in fuel cells should be periodically reviewed.

4.3 Recommended Technologies and Processes

4.3.1 Bio Conversion

4.3.1.1 Single-Stage Anaerobic Digestion

The practice of humans harnessing microbial activity to produce a desired result has been around for thousands of years. The single stage anaerobic digestion of excreta, without heat and mixing, also known as “low rate” digestion, has been used for centuries. Farms have also used biodigesters for many years to recover methane from animal manure. The process consists of three basic steps. The first step is the decomposition of the excreta. This step breaks down the organic waste to working sized molecules. The second step is the conversion of decomposed matter to organic acids. The final step is converting the acids to biogas.

The biogas can be used for electricity, heat or fuel, as described more fully in Section 4.3.2. Anaerobic digestion can also produce raw material by-product streams that can be further refined into higher value products such as soil amendments. In addition, digestion can alleviate many environmental issues, such as water and air pollution, greenhouse gas emissions, and the overall odors and vector attraction. Moreover, digestion can provide a sustainable agricultural product for use as a fertilizer or soil conditioner and potential source of revenue.

A schematic of a low-rate digester is shown in Figure 4-1. Typically the reaction tank consists of a cylindrical, square or rectangular tank with a sloping bottom and a flat or domed roof. Anaerobic digesters in developed countries are typically mixed and heated to increase the microbial growth rate; however, unmixed and unheated systems can also be effective.

Anaerobic digestion can take place in different configurations ranging from individual biodigester toilets to multiple tank configurations. In fact, the application of anaerobic digestion of excreta to produce methane gas was first started in a septic tank. The gas from the first application was collected and used for lighting in and around the plant. The original septic tank concept has been adapted in the following century to promote better anaerobic digestion in a single stage process. Unheated anaerobic digestion requires a minimum tank detention of approximately 20 to 60 days; however, longer detention times increase decomposition and biogas generation. Sewage from one person (or population equivalent) can generate one cubic foot of biogas per day, containing 600 Btu of energy or 2.2 watts of power.

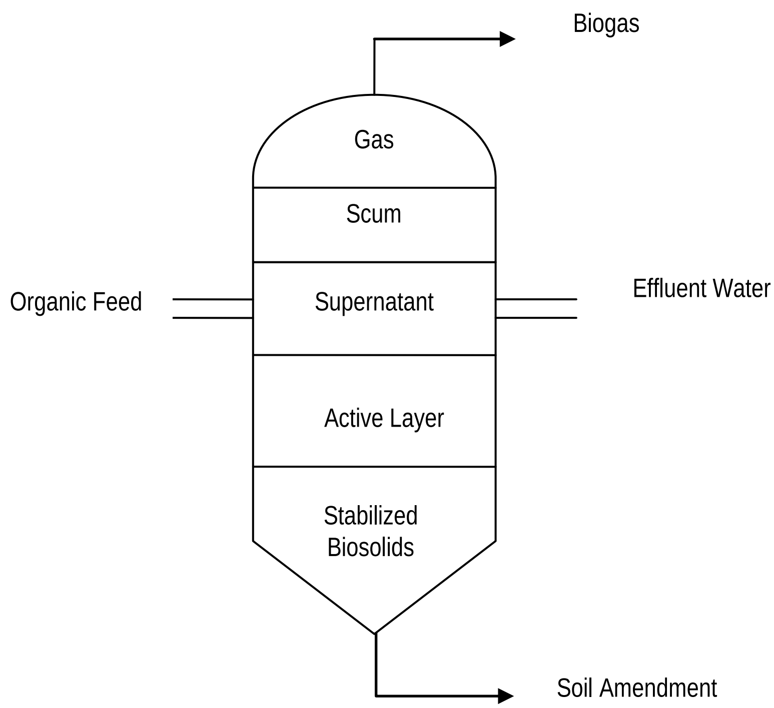


Figure 4-1. Low-Rate Anaerobic Digestion.
Adapted from WERF, 2007.

Because there is no auxiliary mixing, several layers exist in the tank. Rising gas bubbles created through methanogenesis can result in some internal mixing. Biogas that accumulates in the headspace of the tank is collected for storage or use. Scum accumulates on the liquid or supernatant surface. The stabilized solids settle to the bottom for removal and are available for use as a soil amendment. The supernatant is drawn off and may be recycled. Between the supernatant and the stabilized solids is the active layer. Grit and scum will accumulate on the bottom and the liquid surface, respectively, requiring periodic maintenance to retain the original volume.

Anaerobic digestion reduces the pathogens and odor potential in the solids. The residual solids removed from an anaerobic digester can be land applied to recover their nutrient and organic matter or processed further.

Anaerobic digestion has been implemented extensively at the household scale in developing countries, particularly in China and India. Fixed-dome digesters have been used extensively in China since the 1970s, and 15 million households had biogas systems in 2004. Sixty percent of these systems are inactive due to lack of maintenance. Early models were constructed of concrete, but newer plastic models are easier to install and require less maintenance. Companies such as Chongqing Wangliyuan Agricultural Development Co. and

Shenzhen Puxin Technology Co. manufacture models for households, as well as larger industrial systems (alibaba). Several Puxin Biogas Digesters have been installed in Kenya by JuaNguvu Ltd., including one system that processes 10 tons of agricultural waste per day in Tiwi, Kwale (JuaNguvu). The biogas is used for heating and converted to electricity, replacing firewood and diesel for heating and electricity used in an industrial process. In India, more complicated floating dome digesters are commonly used for homes and community toilets. Sulabh International Social Service Organization had installed 150 community systems as of 2004. Both China and India, provide government and corporate support for anaerobic digestion including subsidies, manufacturing and installation services, and technician training. Other anaerobic digestion initiatives include the Biogas Support Program in Nepal, a cooperative effort between the Vietnamese Department of Agriculture and the Netherlands Development Organisation (SNV), and efforts by the Bangladesh Council of Scientific and Industrial Research. CAMARTEC in Tanzania designs small-scale biodigesters and most installations of digesters in East Africa use their design or a modified version of their design.

4.3.1.2 Composting

Composting is an exothermic biological decomposition process that produces a humus-like product with few pathogens. The composted product contains nutrients and organic matter that can be beneficially used to promote plant growth and reduce soil erosion. Composting systems are designed to operate under aerobic conditions. The biology associated with aerobic treatment results in the generation of heat, which is critical to pathogen reduction, seed destruction, and minimization of odors. Adequate detention times are required to ensure sufficient decomposition and pathogen destruction

A successful composting process depends on the use of a “recipe” which provides proper amounts of carbon, nitrogen, moisture and bulking agents. For example, very wet substrate, such as latrine waste, is not sufficiently friable to allow air movement through the material. Conversely, a very dry material, such as straw or hay, will not decompose readily due to lack of moisture for the microbes. Therefore, it is common to use a blend of wet and dry materials to achieve a porous mix with moisture content in the range of 50-60%. The “recipe” must also provide nutrients for biological growth and sufficient biodegradable organics to allow heat buildup within the composting mass. Thus, the starting mixture provides for physical conditioning (porosity), chemical conditioning (water and nutrient), and energy conditioning.

One of the major advantages of composting is its adaptability to a variety of starting substrates. Composting has been applied successfully to kitchen waste, yard waste, animal manures, and a variety of agricultural materials. Latrine waste and kitchen waste should be excellent substrates for composting provided a low moisture “bulking agent” is available to condition the starting mixture. Sawdust, wood chips, straw, agricultural wastes, and even recycled composting itself are common bulking agents. Because the composting process is amenable to different waste materials and can accommodate seasonal waste availability fluctuations, composting provides an excellent opportunity to improve a community’s sanitation and can be implemented at different levels from household to larger-scale centralized facilities.

There are a number of composting configurations used. In its simplest form, the feed mixture is simply placed in piles that are not moved until the process is complete. The size of the pile is limited to ensure adequate oxygen transfer to maintain aerobic conditions. Other configurations include long windrows that must be mechanically agitated or "turned" to incorporate air. A number of "in-vessel" systems are available to further automate the process, reduce odor potential, and increase flexibility in the starting mixture. One noteworthy in-vessel system, provided by Siemens, uses long channels, rectangular in cross-section, with an automated agitator.

Because open piles are subject to inclement weather, and building costs and odor control can drive up facility costs, alternatives include the use of proprietary semi-permeable membranes to cover the compost piles. One integrated cover system is supplied by W.L. Gore and Associates, and includes GORE® semi-permeable cover, in-floor aeration, aeration blowers, oxygen and temperature sensors, controllers, computers, software, and cover handling systems. A similar membrane-cover system is provided by Ag-Bag Environmental that aerates the covered windrows using perforated plastic piping placed on the bottom of the compost pile.

There is a considerable history of composting municipal solid waste in developing countries, though with mixed results. Successful projects include an operation in Maqattam, Egypt, a slum on the outskirts of Cairo. After recyclables are removed, garbage is mixed with pig manure, mechanically sieved, and composted for 6-15 days. The finished product is sold to farmers and the profits cover the operating cost and support associated social development staff. Other successful solid waste projects include one in a neighborhood in East Jakarta, Indonesia, Excel Industries composting operations in India, and large facilities near Sao Paolo, Brazil. Failed projects include a number of sophisticated mechanical plants built in Africa in the 1970s and 1980s which are now inoperable due to lack of technical personnel and mechanical breakdowns. Similarly, a study in 1990 found that of 42 composting locations in Brazil, 24 were closed. Notable issues include unrealistic profit expectations by the municipal managers and poor quality product.

Co-composting fecal sludge with solid waste is less extensive in developing countries, but there are a number of pilot projects. The town of Rini, South Africa (pop. 100,000) mixed latrine sludge and refuse, composted the mixture, and used the product for municipal gardens. The project was closed after five years of operation when the latrines were replaced with sewers. In 1981, a pilot project in Saint Martin, Haiti found that the product of co-composting produced better plant yields than refuse-only compost. Co-composting has been practiced in China, Ghana, Vietnam, and other locations, but has not seen widespread application to date.

Composting should be considered a viable technology, particularly for latrine and kitchen wastes, because of its long history of use, adaptability to different substrates, and production of a useful end product to improve soil fertility. Composting can be accomplished at a small scale and does not require large operations to work well.

4.2.1.3 Vermicomposting

Vermicomposting is the use of earthworms to decompose and stabilize organic materials. Organic materials amenable to vermicomposting include liquid and dewatered wastewater sludges, as well as food, agricultural, and green wastes. The earthworms break down organic material in excreta and food waste while producing fine-grained castings (vermicast), considered by some to have greater value as a soil amendment than traditional compost due to its higher nutrient concentrations readily available for plant uptake. The process is generally operated in a semi-continuous flow to a series of modular beds that are configured to various lengths depending on the feedstock, feed rate, and media necessary to maintain aerobic conditions. The earthworms stay in the bed with no need to restock regularly; generally, the worm population is self regulating and will increase to the point where available food and space constrain further expansion. The process must be monitored for such parameters as moisture content and temperature but is not labor-intensive. Flow of solids into the system is then adjusted to optimize living conditions for the worms. In contrast to conventional aerobic composting, it does not involve a thermophilic stage to achieve stabilization. As with other non-enclosed composting technologies, vermicomposting does have a fairly large footprint similar to aerated static pile composting.

This process is beneficial in facilitating organic solids destruction without releasing objectionable odors, and it produces a safe bio-fertilizer material. Several studies also indicate vermistabilization could be used to dewater as well as stabilize liquid sludges. This holds promise for application in developing countries at the community scale. On the other hand, there are some design and operational challenges that must be considered to control the physical environment of the worms. Optimal conditions for worm growth include bed temperatures of 15-25ºC, sludge moisture content of 80-99%, and pH between 5.5 and 8.5. Aerobic conditions must be present throughout the processing section of the bed. Feed rates of the organic material must be adjusted based on the worm population density. While worms can handle cold, they die when it is too hot, consequently most systems need some sort of cooler in hotter climates. Further, if the initial mix is too dry, heat generated during degradation can cause the entire bed to heat up, requiring a cooling mechanism to keep the worm population alive.

Vermicomposting has application in the developing world. In particular, the Bhawalkar Earthworm Research Institute (BERI) has established six projects in India including one that processes the solid waste and sewage from 500 homes and greywater from an aluminum factory. Other projects use vermicomposting to treat onion residuals and poultry waste. Furthermore, BERI has successfully marketed their compost as "Biogold" and sells it at a higher price than traditional compost.

Vermicomposting should be considered a viable process because it is a simple technology which can be applied using local materials and skills. It produces not only a safe and nutrient-rich compost as a recoverable product, but grows worms which have revenue potential (i.e., as bait). The vermicomposting process has low odors and produces an organic material suitable for sustainable agricultural and soil conditioning purposes. Several studies also indicate vermistabilization could be used to dewater as well as stabilize liquids, such as latrine waste, which holds promise for application in developing countries at the community scale.

4.3.2 Combined Heat and Power Recovery

4.3.2.1 Burn Gas for Heat

Biogas, which contains a combination of methane and carbon dioxide, can be used in a similar fashion to natural gas. The use of biogas for heat production is the most common application. Biogas can be utilized for cooking, lighting through mantle lamps, electricity generation and body warming during winter. Cooking is the most efficient use of biogas. Biogas burners are available in a wide ranging capacity from 8 to 100 ft^3 biogas consumption per hour.

The biogas burns with a blue flame and without soot and odor. The biogas mantle lamp consumes 2-3 ft^3 per hour having illumination capacity equivalent to 40-watt electric bulbs at 220 volt.

Burning biogas for heat should be considered as a viable technology to couple with processes that result in combustible gas products. It is a simple technology already used globally.

4.2.2.2 Stirling Engines

The Stirling engine is an external combustion engine, invented in 1816; however, it was not as successful as the internal combustion engine and was dismissed as a novelty. A Stirling engine operates by cyclic compression and expansion of contained gas (called the working fluid) at different temperatures created by an external heat source, converting heat energy to mechanical work or electricity. When heated with biogas, the gas never comes into contact with moving parts and the engine operates at lower temperatures.

The two main types of Stirling engines are kinematic and free piston. The kinematic engine has pistons attached to a drive mechanism that converts the linear motion of the pistons to a rotary motion. Because they have a crankshaft and flywheel, kinematic engines may replace internal combustion engines to provide shaft power. The free piston engine uses harmonic motion mechanics and usually planar springs. The pistons are mounted in flexures and oscillate freely, without any contact, and therefore without any wear. They can be configured to provide whatever voltage and frequency are required. (WERF, 2007).

Stirling engines are designed to run on a wide range of fuels and there is interest in the use of biogas to run Stirling engines. The only gas pretreatment necessary is moisture removal and compression to 13.8 kPa (2 psi). This can significantly reduce costs in some cases. Any deposit does not damage the engine because there are no pistons, and the low temperature makes regular maintenance easier. Silicon dioxide deposits, common from biogas, do not harm the engine and can be removed during regular maintenance. The engine uses automotive technologies, requiring minimal specialized knowledge to maintain. Emissions are low, and no treatment of exhaust is typically necessary. Stirling engines can be packaged in a modular fashion, allowing easy installation and expandability.

Figure 4-2. 55-kW Biogas-fueled Stirling engine cogeneration plant at the Corvallis wastewater treatment plant in Oregon. Photo by Carollo Engineers www.carollo.com.

The Stirling engine has been demonstrated to perform very well on biogas at the Corvallis Wastewater Reclamation Facility in Corvallis, Oregon. The unit was installed outdoors. The installation is in a residential neighborhood.

Stirling Biopower began marketing Stirling engines in 2009 and is the only manufacturer known to be specializing in digester and landfill gas applications in North America. Additional sources may be available in Europe. The only engine currently sold by Stirling Biopower is

43 kW. Stirling engines are marketed more extensively for use of other heat sources, such as solar, and advances in Stirling engines are expected.

4.3.3 Post Processing and Nutrient Recovery

4.3.3.1 Sustainable Agricultural Soil Amendment

Many of the recommended technologies identified in Table 3-2 produce sustainable and renewable organic material as products that can be an important agricultural resource in emerging countries. The land application of this soil amendment involves spreading on the soil surface or incorporating or injecting the amendment into the soil. Land application of waste-based soil amendment has been practiced for decades and this soil amendment can supplement or replace commercial fertilizers. Nutrients (e.g., nitrogen and phosphorus), micronutrients including essential trace metals (e.g., copper, zinc, molybdenum, boron, calcium, iron, magnesium, and manganese), and organic matter in the biosolids are beneficial for crop production, gardening, forestry, turf growth, landscaping, or other vegetation. The soil amendment is also used to reclaim marginal and damaged (e.g., from floods or fires) lands, used for erosion control, and as a replacement for top soil.

Waste-based soil amendments generally have lower nutrient contents than commercial fertilizers. Biosolids from wastewater treatment sources typically contain 3.2% nitrogen, 2.3% phosphorus, and 0.3% potassium, while commercial fertilizers might contain 5-10% nitrogen, 10% phosphorus, and 5-10% potassium (U.S. EPA, 1999). Nevertheless, the use of this soil amendment conditions the soil and reduces or eliminates the need for commercial fertilizers, as it inherently acts to slowly release these nutrients (as well as micronutrients) thereby reducing the impacts of high levels of excess nutrients entering the environment. Although some organic waste sources contain metals, excreta and food waste do not unless commercial or industrial wastes are mingled with the excreta. Also, chemical fertilizers can contain metals, too, although data on metals in fertilizers are not comprehensive.

Processing or treatment before land application is necessary to create a soil amendment (in contrast to disposal of excreta which is an unsafe practice) and this can involve digestion, composting, alkaline treatment, thermal conditioning, or other methods. Soil amendment products are produced with different levels of safety and suitability for reuse in agriculture. Drier products have less odors and more flexibility in land application due to its higher quality.

The organic material in the product also has very positive impacts on the existing soils. The organic material builds the soil and remains in the soil. Over a period of time, the amount of soil actually increases. If the soil is sandy, the increased organic concentration helps the solid hold the moisture over a longer period of time. In a dry climate, this reduces the need for additional irrigation. If the agriculture soil is a primarily a clay soil, adding the organic material helps the soil drain easily. Having agriculture soils built up and helping the soil hold needed moisture or drain excessive moisture has a significant impact on crop yields in developing countries

CHAPTER 5.0

Applications for Developing Countries

5.1 The Sustainable Sanitation Service Business Model for Developing Countries

The sanitation challenge worldwide has largely been seen as a problem of people not having access to a toilet. The approach to solve this problem has been an overwhelming focus on latrine construction without much consideration for the development of sanitation services that could lead to sustainable sanitation, absent international aid. As a consequence, toilets have been built for some but not others, toilets lie abandoned or broken, and the number of people worldwide without effective sanitation remains astronomical.

Thankfully new approaches are emerging that explore the entire sanitation value chain and are creating opportunities for businesses to emerge to provide an on-going sanitation service to poor families worldwide. These include service models like "Team Clean" in Ghana, Sanergy in Nairobi and some of the newer work of Water For People in places like Uganda, The common theme of all these, and other, business-focused sanitation models is that the combination of a service (sanitary waste processing) with a technology or product. This business model shows promise because there is an on-going relationship between the service provider and the user.

To be successful, a sanitation-based business needs an ongoing relationship with a customer that, if well done, will benefit the customer (clean toilet, recovered energy or product) and the service provider (money). Sanitation management is a business that fits this model. The key is to:

- Get entrepreneurs to see people as customers who want a service at a reasonable price.
- Help with technology for people who live in places with hard access, under difficult conditions.
- Include management guidance (from operation and maintenance of the technology to sale and distribution of the by-products). The success of these technologies either alone or coupled as the Omni-Processor depend upon how well the process is managed.

Lots of innovation is possible for supporting the Omni-Processor vision, but the innovation may not be in finding a 'blue sky' process, but in adapting established technologies in ways to fit developing world communities.

5.2 Omni-Processor as a System

The most promising technologies for the Omni-Processor are not single processes but technologies and processes which can be coupled to convert excreta into recoverable energy and soil amendment products. The series that emerge from this evaluation include:

- The highest reuse potential from human excreta lies in using its stabilized organics (humus), nitrogen, phosphorus, and trace elements to build the soil profile and help achieve sustainable agricultural practices. **Anaerobic digestion** is the key starting process to realize this vision.
- Anaerobic digestion can biologically stabilize the raw organics and produces a valuable biogas in the process. The biogas can be used wherever heat is needed, such as cooking and space heating. More advanced uses of the gas are possible including combined heat and power (CHP) generation (i.e., **Stirling engines** and other CHP alternatives) to recover both heat and electrical energy.
- Anaerobic digestion sets the stage for a number of reuse possibilities that are simply not practical with raw excreta. Liquid digested sludge can be directly applied to agricultural land to recover the nitrogen, phosphorus, trace element, and organic humus values within the material. The combination of anaerobic digestion and proper land and crop management can achieve a low risk of pathogen transport.
- Liquid digested sludge can also be stored in open storage basins (lagoons). This achieves additional pathogen destruction, provides a buffer to help match cropping cycles, and significantly reduces the odor characteristic of the material.
- Anaerobically digested waste can be dried by air, solar, or heat drying. A fully dried material can be stored for extended periods of time to help match cropping cycles.
- If partially dried, the digested waste can be amended with other materials and **composted** to produce a **soil amendment**. A compost product can be stored to match crop cycles, but may find other uses and business potentials such as potting soil. **Vermicomposting** is also possible to further improve the attractiveness of the final product.

5.3 Application to Developing World Scenarios

Additional information and support activities are needed to successfully implement the recommended technologies as part of the Omni-Processor vision. Some recommended activities needed to make the vision successful include:

- Assemble a global list of organizations and individuals engaged in research and implementation of these technologies in developing countries to explore collaboration. Collaboration in future efforts would be beneficial to avoid duplication of efforts.
- Prepare information on the management and worker needs to run these technologies under a successful business model for developing countries. Information should be well thought out and simple to understand as well as translated into local languages. The information may not be written but communicated using short videos or other mixed media.
- Prepare information on handling and management of the soil amendment products in the absence of laboratory testing to confirm pathogen destruction and developed world standards for beneficial use of these products. Same language and distribution media would also apply to a slightly different audience (the farmer or grower, not the management service provider).
- Develop simple models to assess business models, costs, and investment options that will allow sanitation businesses to emerge and possibly thrive.

5.4 Research Needed to Develop Omni-Processor

Research topics remain that need to be addressed before implementation of conversion using anaerobic digestion technologies, coupled with co-generation and soil amendment. These topics include:

- A study to identify the practical, very small scale adaptations needed to improve the performance of community-based anaerobic digester (AD) systems based on international case studies of regions where this technology is being used (China, India, Nepal). A relatively small number of small-scale and community-based AD systems constructed are still in place in some regions (see above), it is important to identify the reasons for this to prevent similar failures in the future, and to build upon instances where these have worked well.
- Explore co-digestion (excreta and food waste) opportunities for various local scenarios to enhance the success of AD systems purely set up for sanitation needs.
- Identify in depth what research is needed to implement AD + Stirling engines or AD + other generator sets as serial technologies run on biogas at an appropriate small scale.
- Examine the advances made to anaerobic digestion at the very small scale for farm use. Identify what improvements and basic design and equipment models have been tested successfully at the smallest scale. Identify which of these would transfer best to developing world and Omni-Processor criteria.
- Estimate disease risk from application of treated (anaerobic digested, composted) human waste to agricultural or other land as a soil amendment and compare with other sources of nutrients (untreated excreta, manure, chemicals).
- Examine the use of biogas to run Stirling engines and the state of the knowledge in Europe. Identify research needs not currently addressed to promote increased implementation and efficiency of this external combustion engine.

5.5 Significant Researchers

Globally, there are many researchers engaged in the technologies and processes discussed in this report. A primary source of the names of significant researchers is the citations in the numerous literature references. Within the scope of this report, there is a short list of significant researchers who have a long relationship with WERF and our expert advisors in Appendix B.

The following organizations are excellent resources and sources of expertise in topic helpful to achieving the Omni-Processor vision:

The International Water Association (IWA) has a Specialty Group on Anaerobic Digestion (http://www.iwahq.org/78/networks/specialist-groups/list-of-groups/anaerobic-digestion.html).

SNV (Netherlands Development Organization) (www.snvworld.org)

UNICEF (School WASH programs)

UN-Habitat

WaterAid

IRC Netherlands

UNESCO-IHE

SuSaNa (Sustainable Sanitation Alliance)

EAWAG-SANDEC (http://www.sandec.ch/index_EN)

APPENDIX A

BRIEF DESCRIPTIONS OF TECHNOLOGIES EVALUATED

A.1 Energy Recovery

The following technologies and equipment summarized below produce materials to recover energy from excreta and residential organic waste, such as food waste. These technologies formed the basis of the universe of technologies examined in this study.

A.1.1 Bio Conversion

Processes that use microorganisms to break down organic compounds and produce cellular material which can be further used as a source for energy and nutrients are categorized under Bio Conversion. Some of these processes are aerobic (with oxygen) and anaerobic (without oxygen).

A.1.1.1 Aerobic Digestion

Aerobic digestion is an aerobic process. The process reduces the biodegradable solids, reduces the potential for odors, and reduces the number of pathogenic organisms in the excreta by bacteria that require air (oxygen) to grow and metabolize the raw materials. The process produces stabilized solids, usually cellular material from the microbial growth, CO_2, and water. The process requires compressors, pumps, piping, and tankage to ensure that adequate air is available for microbial decomposition of the raw material. The high outside energy requirements and complexity eliminates the process from further consideration.

A.1.1.2 Anaerobic Digestion

Anaerobic digestion is a process that breaks down organic material in excreta and food waste in the absence of oxygen. This process produces biogas (a gas which is approximately 65% methane), $CO_{2,}$ and stabilized solids. The methane from the biogas is a key source of renewable, recoverable energy from excreta. This process can be a simple, unheated, single stage unit or can be optimized to improve gas conversion by complex, heated, multiple stage processes.

Single-Stage

In the mid-1800s, anaerobic digestion processes for sanitary wastes were developed in Europe after observing this naturally occurring process in decaying organic matter. In its most basic form, it is unheated, unmixed decomposition of wastes in tanks without oxygen. Since the produced biogas has value, new designs of the single stage process capture the biogas for energy recovery. Advances have also been made to adapt anaerobic digestion processes to small scale applications, particularly for the farm. This technology is suitable for the Omni-Processor vision and is described in detail in Chapter 4.0.

Multiple-Stage

In the mid-1900s, heating, mixing, and a second stage was added. This reduces the treatment time and increased gas production. Several variations of the basic anaerobic digestion process have been developed in recent years, several of which use multiple stages in series. These include: 1) temperature phased anaerobic digestion (TPAD) using thermophilic and mesophilic reactors in series; 2) acid phase digestion that separates the acid and methane formation phases; 3) two-phase digestion that uses an aerobic first-stage to autothermally heat the material prior to digestion; 4) processes that combine a first-stage continuous feed with a batch operated second-stage to improve pathogen destruction; and 5) pre-processing by heat (thermal hydrolysis) or other means to improve biodegradability. Each of these variations offers certain advantages, but they all increase the complexity of the basic process and were eliminated.

Lagooning/Storage

The Department of Water and Sanitation in Developing Countries (SANDEC) at the Swiss Federal Institute for Science and Technology (EAWAG) has supported several fecal sludge treatment facilities utilizing dry beds and lagoons for treatment of public toilet waste, latrine sludge, and septage. In Kumasi, Ghana, a city of one million people, the latrines and public toilets are emptied by 17 trucks from five different private companies and the local government, and then delivered to a lagoon treatment plant near town. SANDEC reports that consistent service has been an issue due to unclear division of responsibilities between the public and private agencies. The city of Bamako, Mali has a history of private providers of sanitation services. Beginning with subscription-based collection of solid wastes, organizations such as GIE Sema Saniya have since expanded their operations to include sludge collection with trucks and tractor drawn pumps and construction of a lagoon fecal sludge treatment plant. They provide regular solid waste pickups and employ commission based collection agents to collect subscriptions, and report a 90% payment rate in all neighborhoods. Latrine emptying is provided on a fee per empty basis, and the GIE has taken their own initiative to construct a treatment plant to serve two of the 12 communes of the city with cooperation from a Peace Corp volunteer. SANDEC has consulted on similar projects in Vientiane, Laos, Nam Dinh, Vietnam, and others.

This approach may be applicable in certain developing world circumstances, but it did not meet the criteria for the Omni-Processor, certainly for location in a neighborhood-based community setting or requiring a small footprint.

Plug Flow

This process is based upon the basic anaerobic digestion process, except this is operated with laminar plug flow instead of complete mixing through the unit. It requires chemicals to be added to control pH during the process. This process increases the destruction of total solids within a 24-hour detention time, however, this is a complex anaerobic digestion process not suitable for developing communities with basic skill levels. One such process was developed by the University of Louisiana, but there are various other commercial Plug-Flow type technologies developed over the years.

Plug-Flow Thermophilic

This is laminar, plug-flow anaerobic digestion at thermophilic (heated) temperatures. This process configuration increases pathogen reduction and biogas production. From an emerging country perspective, this is a complex process which includes heating the digesters for thermophilic digestion. This is a complex anaerobic digestion process not suitable for developing communities with basic skill levels.

In-situ Landfill Digestion (Urban Waste and Sludge)

Landfilling generally is regarded as a "disposal only" method of waste management. Refuse placed in a landfill will decompose slowly. If the landfill is properly covered, the interior will be anaerobic. Biological decomposition will produce methane and carbon dioxide (biogas) as end products. If these end products escape to the atmosphere, then the landfill is truly a "disposal only" method of management. The release of methane is particularly undesirable because it is a potent greenhouse gas. Nevertheless, landfilling continues to be practiced around the world because it is relatively inexpensive, does not require a high level of technology, and removes the waste from human contact.

The situation can be viewed differently if biogas from the landfill is collected and used as fuel. In this way the landfill becomes a form of in-situ anaerobic digester. Rather than a bioreactor designed of concrete and steel, the landfill itself becomes an "earth reactor". One problem in using a landfill as an "earth reactor" is that the environment inside the landfill is not conducive to rapid biological decomposition. Conditions are usually dry because the starting refuse itself is dry and rain water cannot easily penetrate the landfill except in very wet climates or areas of high groundwater. Municipal refuse often lacks essential macro-nutrients, such as nitrogen and phosphorus, particularly if kitchen wastes are removed. Finally, refuse is largely cellulosic and does not buffer against the high carbon dioxide concentrations in the biogas. The pH is depressed as a result and low pH is a serious limitation to biogas production. All of these factors discourage decomposition in a typical landfill.

The addition of latrine wastes to a landfill can accelerate decomposition and improve biogas production. First, additional biodegradable organics are added from the latrine waste. Second, the high moisture content adds water which usually is lacking. Latrine waste is also high in both nitrogen and phosphorus. Finally, latrine waste is high in protein which produces alkalinity within the landfill to buffer the low pH. For these reasons, a refuse landfill receiving municipal sludge normally produces more biogas than a comparable landfill without sludge. Additional strategies are possible to enhance in situ digestion of solid waste and are discussed in literature on bioreactor landfills. On the downside, the biogas collection system can be a challenge particularly if the landfill is large or not originally designed for gas collection. Nevertheless, whether landfilling is disposal or reuse depends largely on whether biogas production is encouraged and whether it is collected and used as a renewable fuel source.

A.1.1.3 Composting

Haug (1993) defined composting as the biological decomposition and stabilization of organic substrates, under conditions that allow development of thermophilic temperatures as a result of biologically produced heat, to produce a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land. A wide variety of technologies have to applied to composting, ranging from simple static piles to turned windrows to more complex "in-vessel" systems. One advantage of composting is that it can be applied to a variety of waste materials, including fecal wastes, kitchen wastes, animal manures, and yard and agricultural wastes. As generally practiced, composting systems are designed to achieve aerobic conditions to the extent possible. Experiments have been conducted with anaerobic composting but it is not widely practiced.

Composting is discussed in detail in Chapter 4.0 as a recommended process.

A.1.1.4 Wetlands Treatment of Wastewater Solids

Constructed wetlands utilize biological activity to treat wastewater sludge, and can include above ground flow as well as subsurface flow. Above ground flow wetlands are ponds with a maximum depth of 1.5 meters, and free floating plants or reeds growing throughout. The extensive root system of plants like water hyacinth provides a large surface for microorganisms to grow on, leading to more efficient treatment than similar lagoon systems. Subsurface flow wetlands commonly have a drainage layer of gravel, a layer of permeable sand, and then a top layer of permeable soil with appropriate plants. Constructed wetlands are well established in the developed world and their use is growing in developing countries in Africa and Asia, ranging in size from those serving a few hundred people to those serving several thousand. Commonly used plants include water hyacinth, cattails, water spinach, Napier grass, and papyrus reeds.

Much like lagoon treatment systems, constructed wetlands are very appropriate for developing countries. They require no electricity if designed to drain without pumping and produce largely pathogen-free water and solids, useful for agricultural application. Construction materials such as sand and gravel are commonly available, and no mechanical apparatus is needed apart from drainage pipes. But also like lagoon systems, constructed wetlands require a large land area, commonly several square meters per capita. They also require regular maintenance to harvest the rapidly growing plants as well as disposal of the generated biomass. This biomass can be used to increase biogas generation in an anaerobic digester. Potential problems with constructed wetlands include pests such as mosquitoes or water snakes, occasional odors, and the need for careful selection of the vegetation. Water hyacinth, in particular, can be an invasive species if not controlled effectively. Native vegetation is recommended to ensure ecological protection and adaptation to the climate.

This approach may be applicable in certain developing world circumstances, but it did not meet the criteria for the Omni-Processor, certainly for location in a neighborhood-based community setting or requiring a small foot print.

A.1.1.5 Vermicomposting

This process uses earthworms to reduce the volatile solids in waste organic matter such as excreta and food waste. This process produces a dried, nutrient rich material. Vermicomposting is accomplished using excreta in beds that are populated with earth worms. This is a simple process and not labor intensive. The castings form the earthworms are nutrient rich soil and very valuable. This technology is discussed in depth in Chapter 4.0.

A.1.2 Thermal Conversion

The following section discusses thermal conversion processes. In this category of process, there are some attributes common to many of these technologies. A common problem is that most thermal conversion processes (exceptions noted below) require drying of the raw material (i.e. latrine waste (99-95% water), food waste, etc.) in order to work. Producing dried raw material presents problems in operations, including high energy requirements and cost implications. These processes typically require energy (outside power or fuel) to operate, at least at start up. The outside energy requirements may be considerable.

A.1.2.1 Sludge to Liquid Fuel

In theory, dried fecal material can be thermally processed, either by pyrolysis (no air) or gasification (partial air) to produce a liquid, storable fuel. Some attempts have been made to achieve this in practice on municipal sludges. However, none have achieved commercial success. The processes required to produce a useable liquid fuel are complex, technically sophisticated, and have not demonstrated success in small applications.

A.1.2.2 Sludge to Syngas

Steam/CO_2 Reforming

Steam/CO_2 reforming, a process that has been used in other applications for 100 years, can be used to convert organic solids (such as excreta and food waste) to hydrogen, a renewable fuel. Organic waste is introduced into a reactor with minimal air. The waste is mixed with CO_2 and steam at 500^o centigrade, resulting in a residual solid and a synthetic gas. The gas is further heated to 1000^o and breaks down into hydrogen and CO. The hydrogen is purified and the CO recycled into the process. The hydrogen can be used by a fuel cell to generate electricity which will run the process. Waste heat can also be recycled and excess hydrogen or electricity can be sold.

Advantages include the ability to use materials with high water content, so drying is not required for this process. Although the system uses high temperatures, the process does not involve combustion. Disadvantages are that it is marketed by a single firm (Intellergy) with process improvements that are proprietary. This process is promoted by the developer as self sustaining without outside power after start up but has not been proven to work on excreta or wastewater process solids. A California Energy Commission demonstration project applying this technology to wastewater solids is pending by the San Francisco Bay Area Biosolids to Energy Coalition but it is not underway yet.

Gasification

Gasification, sometimes called partial oxidation, is the thermal conversion of carbonaceous biomass into a combustible gaseous product, known as syngas, composed mainly of hydrogen (H2), CO, CO_2, water, methane (CH_4), and N_2. Partial oxidation lies between the extremes of combustion and pyrolysis (no oxygen).

Depending on the gasification process, higher hydrocarbons such as tar can also be present in the syngas. Conversion of the solid fuel to syngas is accomplished by heating the biomass to high temperatures of 500-1600°C, under pressures ranging from atmospheric to 60 bar in the presence of a gasifying agent and a controlled supply of oxygen.

Gasification was eliminated from further consideration because it is energy intensive to run and needs outside power for start up, it is complex to operate and the equipment is often proprietary and costly.

Pyrolysis

In contrast to incineration (combustion), which works with excess oxygen to achieve the complete oxidation of the organic feedstock and the maximum generation of heat, pyrolysis uses high temperature and pressure (but usually lower than incineration and gasification) in the absence of oxygen to destruct the organic sludge material and convert it into gas, bio-oil, or char, which are products usable for energy recovery.

Pyrolysis is a relatively innovative technology for sewage solids treatment. While a number of pyrolysis facilities exist for biomass (wood chips, etc.) treatment, there are no systems in operation for sewage solids at this time. Although potential energy and resource recovery from pyrolysis is intriguing, the associated mechanical and operational complexity, similar to the other thermal conversion technologies, hinder its viability based on the Omni-Processor criteria.

A.1.2.3 Sludge to Heat

Incineration

Incineration, also called thermal oxidation, is the process of converting organic material at high temperature in the presence of oxygen to heat and ash. Incineration of wastewater solids has been commonly used as an energy recovery and waste minimization method in Japan, North America, and the European Union. Incineration involves five processing steps: dewatering, drying, combustion, control of air emissions, and management of the remaining ash.

On a dry basis, solids after digestion have an energy value similar to that of lignite coal, but the heating value of wet sludge is much lower due to the water content. Supplemental fuel is required if the moisture content of the feed solids is too high to support autogenous (no auxiliary fuel use) combustion. Therefore, wastewater solids generally need to be dewatered to 26-35% total solids (TS) to be autogenous. During incineration, water is initially evaporated; with the combustion occurring after sufficient water is removed and the volatile material reaches combustion temperature. Combustion is an exothermic reaction during which the volatile fraction of the solids is destroyed, resulting in the production of hot gases. The non-volatile (inert) part of the sludge results in ash.

Thermal energy can be recovered from the high temperature flue gas. The combustion process also produces air emissions consisting of particulates, nitrogen oxides (NOx), carbon monoxide (CO), sulfur oxides (SOx) and metals including mercury (Hg) that need to be removed. NOx and SOx can react with water vapor to form acid rain. Ash produced from the incineration process consists primarily of the inert solids in the incinerator feed and is approximately 20-50% of the dry solids. The volume of ash produced is often 10-15% of that of the sludge combusted, reducing the amount of material for disposal or reuse. Ash is sterile and is easier to handle than wet sludge.

A variety of technologies are used for incineration, with the predominant technologies being multiple hearth incinerators (MHI) and fluidized-bed incinerators (FBI). While incineration technologies offer numerous benefits, such as energy production and solids minimization with minimal quantities of ash, this technology is mechanically complex, and requires supplemental fuel at times, and a solids production threshold of approximately 50 dry tons per day to be economically viable.

Vitrification

This process, also called glassification, converts waste to glass material. The process operates at 3000°F, destroys organics and melts the inorganics producing a glass aggregate. The glass aggregate has many reuse options.

This technology requires significant amount of electricity and fuel to heat the solids to a melting point. It is a complex technology which was eliminated from further consideration.

Vitrification was eliminated from further consideration because it is energy intensive to run and needs outside power for start up, it is complex to operate, and the equipment is proprietary and costly. One application of this technology was in operation at the North Shore Sanitary District, IL, but the original vendor is no longer making this technology.

Plasma

This is a proprietary oxidation technology. It operates at a temperature of 500-600^{o}C at atmosphere pressure. The plasma arc generates ultraviolet radiation to produce ash. This process requires significant electricity for the plasma arc and is a complex technology. Plasma technology was eliminated from further consideration because it is energy intensive to run and needs outside power for start up, it is complex to operate and the equipment is often proprietary and costly.

Super-Critical Oxidation

Super-critical Water Oxidation (SCWO) process involves taking any liquid substance at a temperature and pressure above its critical point, where distinct liquid and gas phases do not exist. The critical point for water is about 375^{o}C and 217 atm pressure (3,200 psi). Under these conditions, the liquid/steam mixture acts as a very efficient solvent and attempts have been made to take advantage of this property to oxidize organics. Pure oxygen must also be supplied at this pressure to provide an oxidant for liquid phase combustion of the organics. This is basically a thermal process where the combustion takes place in the liquid phase. A pilot facility in Florida is designed to operate at 590^{o}C and 3,200 psi (Haug, 2009).

This is an emerging technology with little operational or cost data for full scale systems. Supercritical water oxidation is an extremely complex technology. SCWO is expected to be more expensive and is less proven than incineration technologies.

Low-Tech Combustion

Thermal processing normally is a complex technology involving combustion vessels, air supply fans, fuel burners, heat exchangers, and a variety of air pollution control systems. However, combustion can also be carried out using relatively low technology. For example, dried fecal material can be used as fuel in a stove for heat or cooking. If mixed with refuse or other dry material, the waste can be placed on a simple grate with wire mesh sides and then lit by torch or match. This is not an elegant process and it will discharge smoke and other air pollutants. However, the material is eliminated and the ash that remains is easier to dispose or possible reuse for its nutrient value.

A.1.3 Combined Heat and Power Recovery

Many of the conversion technologies result in the production of a combustible gas. Anaerobic processes result in biogas, which is about 65% methane, similar to natural gas. The thermal conversion processes produce a synthetic gas or liquids which may be combustible mixtures of CO, other carbon compounds, and even hydrogen gas. To recovery the heat and power from these byproducts, other technologies are coupled. The fuel products can be used by the Combined Heat and Power (CHP) recovery technologies to produce usable heat and mechanical or electric power. The heat is often recycled back in a loop to operate the conversion technology while the power can be used or sold.

A.1.3.1 Burn Gas for Heat

Biogas can be utilized for cooking, lighting through mantle lamps, electricity generation and body warming during winter. Cooking is the most efficient use of biogas. Biogas burners are available in a wide ranging capacity from 8 cft to 100 ft^3 biogas consumption per hour. The biogas burns with a blue flame and without soot and odor. The biogas mantle lamp consumes 2-3 ft^3 per hour having illumination capacity equivalent to 40-watt electric bulbs at 220 volt.

A.1.3.2 Internal Combustion Engine

Digester gas has been used for many years in internal combustion engines that drive electricity generators. When heat is recovered from the engine/generator set, the process is called cogeneration. Companies such as Waukesha, Cummins, Cooper, Caterpillar, and Jenbacher manufacture gas engines for cogeneration running on digester gas. New generation, lean burn engines have higher efficiency.

A.1.3.3 Fuel Cells

Fuel cells are an emerging energy recovery technology which converts the chemical energy in hydrogen or a hydrocarbon fuel (biogas) with oxygen or other oxidant over an electrolyte to produce electricity and heat. Fuel cells can be operated in environmentally sensitive areas because they produce very low air emissions. The U.S. Department of Energy and other organizations are funding considerable research into improvements in fuel cell technologies.

A.1.3.4 Turbines (Steam)

Steam turbines or boilers are one of the original methods for energy (heat) recovery from digester gas. Boilers are robust recovery devices, requiring little in the way of gas pretreatment. Digester gas is combusted to produce hot water or steam. The recovered heat can be used to maintain the anaerobic digester temperature using heat exchangers or direct steam injection, and also for space heating. Boilers required trained operators.

A.1.3.5 Turbines (Combustion)

Combustion gas turbines use digester gas to generate heat and electric power. These turbines consist of three sections: a turbo compressor to compress air; a combustion chamber where the gas ignites; and a turbine which extracts mechanical energy to produce electric power and to drive the compressor.

Microturbines are a newer, much smaller version of combustion gas turbines. The combusted gas drives turbine fan blades on the shaft, which rotates through the generator section. The microturbines are modular machines with improved efficiency but require gas or high quality. The main providers of microturbines operating on digester gas are Capstone and Ingersoll-Rand.

A.1.3.6 Stirling Engines

The Stirling engine is an external combustion engine, invented in 1816. While it has been around for almost 200 years, it was not generally competitive with the internal combustion engine, and was considered a novelty except in certain recent applications. A Stirling engine operates by cyclic compression and expansion of contained gas, called the working fluid, at different temperatures by an external heat source such that there is a net conversion of heat energy to mechanical work or conversion to electricity. When heated with biogas, the gas never comes into contact with moving parts and the engine operates at lower temperatures. Any deposit does not damage the engine because there are no pistons, and the low temperature makes regular maintenance easier. This eliminates most pretreatment of digester gas.

Stirling Biopower began marketing Stirling engines in 2009 and is the only U.S. manufacturer known to be specializing in digester and landfill gas applications. The only engine currently sold by Stirling Biopower is 43 kW. Stirling engines are marketed for other heat sources, such as solar, and advances in Stirling engines are expected.

A.2 Soil Amendments

There are several important components in excreta that make this an important agriculture resource when properly processed. When organic solids are mixed with sandy soil, the organic content helps the soils holds water better. When mixed with clay soil, it breaks the soil up, so the solid drains better. Excreta contains several micronutrients, such as copper, zinc, magnesium, and selenium that improve the health of agricultural plants. However the most important nutrients are Nitrogen (N), Phosphorus (P), and Potassium (K). These nutrients are actually inexpensive, slow release fertilizer materials that will increase the crop yield, feeding more people. Also, the value of the nutrients helps create businesses and revenues, while improving sanitation and hygiene.

The following technologies and equipment summarized below primarily produce materials to recover nutrients from excreta and residential organic waste, although some of these materials, when dried, can be burned to recover heat. These technologies formed the basis of the universe of technologies examined in this study.

A.2.1 Processing Technologies

A.2.1.1 Thermal Drying

Excreta waste, particularly latrine waste, is often wet and semi-fluid in nature. Removal of the water from either raw or digested fecal matter can increase the range of potential uses for the material. Thermal drying uses heat from the combustion of a fuel to evaporate water from the fecal matter. Thermal drying can be either direct or in-direct. For direct drying, the hot combustion gases directly contact the drying material. For indirect drying, the combustion gases typically heat a transfer fluid which is then used to exchange heat into the dryer. Both types of dryers have seen considerable commercial success. Indirect drying may offer some advantages in less developed countries because the technology is more adaptable to skid mounted equipment. An important requirement for thermal drying is the production of a pelletized product which is more attractive and reduces problems associated with a dusty material. With fecal material, thermal drying has been most often applied after anaerobic digestion.

A.2.1.2 Air Drying (Open/Covered)

Air drying is a simple system that allows the solids to dry naturally in the open air. Generally, wet solids are applied to sand beds, paved or unpaved basins to a depth of about 10 inches or more, respectively. The liquid is left to drain and dry by evaporation. Sand beds have an underlying drainage system, while basins require some type of mechanical turning or agitation to facilitate drying. The effectiveness of this drying process depends on the local climate. Covers help to keep the beds dry by minimizing the addition of water through precipitation. If the average temperature of the solids layer is above 0°C on a daily basis for at least 60 of 90 days, harmful pathogenic bacteria and viruses are reduced sufficiently to meet U.S. EPA criteria for a Process to Significant Reduce Pathogens (PSRP). Although land intensive, this process is a low-tech way to dewater and store sludge so that the dried cake with soil-like characteristics can be used as a fertilizer or substitute soil.

Air drying of excreta is a flexible and effective means to dewater and subsequently use the dried product (around 60% total solids) as a fertilizer or soil conditioner. Harmful pathogens are removed by a combination of drying and temperature. The process is amenable to different capacities from the household/community level to even large scale operations. Benefits include the following:

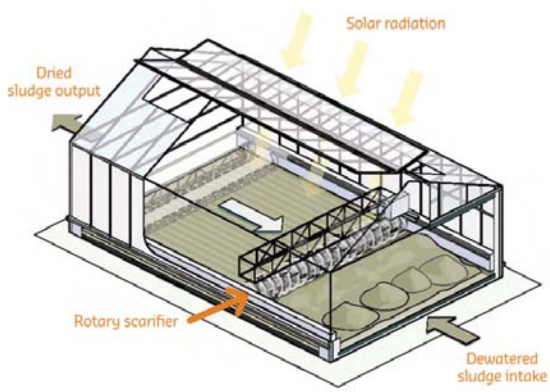
- Household or community levels, although urine-diversion toilets are required for the dry collection of feces, as dewatering without urine-diversion works only in very dry climates.
- Performance. Depends on ambient conditions to control temperature and drying; the process takes place over several months to years and can be enhanced through covers for rain protection (ventilated vaults, covered beds, or even storage in old rice bags).
- Costs. Moderate investment costs depending on the type and capacity of the process, mostly depending on the collection process (e.g., diversion toilets). Capital and operations costs are low in comparison to other treatment processes, and a beneficial product can be returned to the community or sold.
- Compatibility/Operations. Does not require any special equipment although the process can be enhanced through agitation drying using equipment such as a tractor with a horizontal auger or tiller. If necessary and available, addition of alkaline material (e.g., lime) or other bulking material such as sawdust or wood products can aid in the drying process and produce a nutrient-rich organic product for use in the community.

The biggest strength of air drying is its low maintenance and costs with the production of nutrient-rich, organic product to boost local agriculture or soil conditions. Its main weakness, however, is that poor maintenance can quickly lead to nuisance problems such as odors and flies. Air drying is not appropriate for the Omni-Processor unless coupled with anaerobic digestion for post air drying solids drying.

A.2.1.3 Solar Drying (Open/Covered)

Solar drying encompasses many technologies, from simply laying out sludge in the sun to use of greenhouse-style buildings that enhance solar heating, to complicated heat transfer apparatus to transfer solar energy to sludge. In the early 1900s, open drying beds were used for wastewater solids drying. The public would use material from drying beds for agriculture purposes.

The drying process can be very simple or complex. The fundamental principle of solar drying is to use solar radiation and ambient air to evaporate the water contained within the sludge. A solar sludge drying facility normally consists of a climate controlled greenhouse, mechanisms to spread, agitate, and collect sludge. An odor control system might be needed when unstabilized sludge is treated. Auxiliary heating is sometimes provided to facilitate sludge drying during cold seasons. Solar drying produces dry, granular product with solids contents up to 80-90% or depending on the final use requirement. The product can be used as fuel or fertilizer. Studies have shown that solar drying is effective in pathogen and vector attraction reduction and is capable of meeting the highest U.S. EPA standards.



Schematic of a Sludge Solar Drying Facility.
Courtesy of Infilco.

Compared to gas-fired dryers, the major advantages of a solar dryer are its low energy consumption and easy operation and maintenance. Studies have shown that the electrical energy for a solar drying is 20-40 kWh per ton of evaporated water, as compared to 90-120 kWh per ton of evaporated water for a gas-fired dryer. Furthermore, the thermal energy to evaporate water (approximately 3.1 million Btu/ton water evaporated) is virtually free.

The major disadvantage is its relatively large footprint. The required footprint of a solar drying plant depends on the climatic conditions (solar radiation, temperature, humidity, etc.), feed sludge and targeted dried sludge solids content. Without the assistant of auxiliary heating, footprint of the plant could be relatively large. Auxiliary heating can greatly reduce the footprint of a solar sludge drying facility but will increase its energy consumption.

There are several hundred solar sludge drying plants currently in operation around the world, most of which are for small to mid-sized wastewater treatment plants. Currently, the largest solar drying plant for sewage sludge is operating in Palma de Mallorca, Spain. The plant covers a total area of 20,000 m^2 (215,000 ft^2) and has a capacity of 600,000 Population Equivalent (PE), or approximately 40 million U.S. gallons per day (mgd). The largest solar drying plant with auxiliary heating is in Oldenburg, Germany. This plant has a designed capacity of 550,000 PE and requires 6,000 m^2 of plant area.

One such advanced system was tested at the Alexandria, Egypt metropolitan wastewater facility. A solar collector and heat exchanger were used to dry and disinfect sludge following primary treatment and secondary treatment. Documentation of simpler solar drying technologies in the developing world is limited, possibly because drying is typically a post-treatment process. However, low-energy, low-technology solar drying systems have been installed throughout Europe. Degremont's Heliantis system uses a greenhouse combined with a simple mechanical turning apparatus to serve populations of 5,000-50,000. In tropical climates, it is expected that their system would work more efficiently than in Europe, thus requiring a smaller footprint.

There have been several improvements to the traditional drying beds: covered to accommodate rainfall; odor control systems; and sophisticated mixers. Solar drying technologies are available from several vendors including Infilco's Heliantis™, Veolia's Solia™, Parkson's Thermo-System™, and Huber's SRT process. Each technology differs in the way sludge is fed and distributed in the greenhouse. For example, sludge is laid out in windrows in the Solia™, while the Thermo-System™ uses a fully automatic electric mole to spread and turn sludge. Both Infilco's Heliantis™ process and Parkson's Thermo-System™ have over 100 installations worldwide.

This technology has been eliminated for consideration as the Omni-Processor as open drying raw excreta can be very odorous and have health concerns. However, drying digested solids, in many instances, will significantly reduce any remaining pathogens and do so with few odors. With the appropriate climactic conditions and exposure to sun and air, these solids will dry to a product that will be available for fuel and nutrient recovery.

A.2.1.4 Lime Stabilization

Mixing lime with process residuals is a simple process. It was used by the Romans 20 centuries ago to reduce the odor. This process eliminates odors by stopping microorganism activity. Combining lime with solids produces a high pH level (> 11.0) that will reduce pathogen concentration and activity. However, when the high pH gradually reduces, often micro organism activity reoccurs.

Applying lime stabilized product to an acid soil is helpful as an agriculture product. It should not be applied to alkaline soil to prevent raising soil pH to a level that prevents plant growth. The other key concern about the sustainability of this process is the local availability the lime.

A.2.2 Nitrogen, Phosphorus, Potassium (Fertilizer N, P, K) Recovery

All three nutrients are important for plant health, however plants usually do not require significant amounts of potassium. In most regions, nitrogen is the most important nutrient for crop growth.

A.2.2.1 Land Application of Soil Amendment

Land application of post-processed residuals from the conversion processes as a soil amendment is not a technology but is a beneficial use practice where stabilized and safe materials are used as a agricultural fertilizer. Products suitable for land application to produce a valuable fertilizer are produced from virtually all technologies, except incineration. This includes wet residual solids from anaerobic digestion, lagoon treatment, and dried material from air and solar drying, and all types of composting.

A.2.2.2 Nitrogen Recovery

Sometimes, extracting N from a concentrated side stream could be useful. The Ammonia Recovery Process (ARP) was developed by Battelle Memorial Institute. It is used to extract ammonium sulfate form a high strength concentration from a side stream, such as from the centrifuge dewatering anaerobic digested solids. The pilot testing was completed in 1998, but there are none in operation now.

A.2.2.3 Phosphorus Recovery

There are several technologies that could extract P from excrete or side streams at a wastewater treatment plant. These technologies are usually all complicated and required significant operational training. Also, construction and operating costs are significant. These are not suitable as Omni-Processor or discussed in depth. See WERF report INFR4SG09b for a detailed description of these processes.

A.2.2.4 Urine Diversion and Nutrient Recovery

Anthropogenic urine comprises only 1% of domestic wastewater, but contributes 75-80% of the nitrogen, 50-55% of the phosphorus, and a substantial portion of the pharmaceuticals/ hormones and subsequent metabolites. As a result, research to date (largely conducted in Europe) has focused on the potential for urine diversion to reduce the environmental impact of these contaminants, decrease the energy and cost requirements of wastewater treatment, and provide a means to close the anthropogenic nutrient cycle either through nutrient recovery or direct urine reuse. Urine diversion toilets (NoMix toilets) and waterless urinals have been developed by several manufacturers and have been improved through European pilot project feedback. Additionally, urine treatment technologies have been developed to the point of inclusion into small and mid-scale pilot projects. The most notable of which are the use of struvite precipitation at GTZ headquarters in Eschborn, Germany and the use of electrodialysis and ozonation at the Basel-Canton Library in Switzerland. These projects are managed by Ecosan and Eawag, respectively; two of the predominant research groups engaged in urine diversion technological and social development. User feedback has been a crucial part of the development of urine diversion, as toilet use is a sensitive topic. A review of European pilot projects indicates that 80% of users like the idea of urine diversion, 75-85% were satisfied with design, hygiene, and seating comfort of NoMix toilets, 85% thought that urine-based fertilizer was a good idea (50% of farmers), and 70% would purchase food grown with urine-based fertilizer. However, 60% of users also encountered problems, indicating that NoMix toilets require further development. Research and pilot projects have also explored the potential for direct urine reuse, with development of storage parameters to ensure sanitization as well as study of plant yield when utilizing urine as fertilizer. Urine diversion technology is developed to the point that, with proper operation and maintenance, mid- to large-scale pilot projects are possible. However, in addition to necessary improvements or adaptations to urine diversion toilets, several knowledge gaps exist which may hinder the progress of urine diversion in the U.S. Specifically, whole life costs of urine diversion on several scales and life cycle assessments with energy, contaminant, and water balances may be necessary to justify further research. These assessments may take into account other decentralized wastewater treatment scenarios, and should account for the potential to address aging and deteriorating U.S. wastewater infrastructure in a sustainable manner. Pilot projects and social surveys, although extensively conducted in Europe, are lacking in the U.S. These may be conducted either after a simplified set of life cycle and cost assessments is executed, or during the development of more thorough assessments.

Table A.1 Technologies Available for Primary Urine Treatment Goals.
From WERF INFR4SG09b.

TREATMENT GOAL	PROPOSED TECHNOLOGIES (that have at least advanced to lab-scale experiments)	TECHNOLOGIES IMPLEMENTED IN URINE DIVERSION PILOT PROJECTS
Sterilization	Storage	Storage
Stabilization	Acidification, Partial Nitrification	
Volume Reduction to Concentrate Nutrients	Evaporation, Freeze-Thaw, Reverse Osmosis	Evaporation
Nutrient Removal	Annamox (N removal), Electrocoagulation (P removal)	
Phosphorus Recovery	Struvite Precipitation	Struvite Precipitation
Nitrogen Recovery	Ammonia Stripping, Ion Exchange, IBDU Precipitation, Struvite Precipitation	Struvite Precipitation
Removal of Micropollutants	Ozonation, Electrodialysis, Nanofiltration	
Creating a Fertilizer Free of Micropollutants	Struvite Precipitation, Electrodialysis and Ozonation,	Struvite Precipitation, Electrodialysis and Ozonation
Optimizing Nitrogen and Phosphorus Recovery	Struvite Precipitation with Zeolite Adsorption	

APPENDIX B

BRIEF DESCRIPTIONS OF UNIVERSITY RESEARCHERS AND TECHNOLOGY DEVELOPERS

B.1 Anaerobic Digester and Composting Research

Many universities conduct research on anaerobic digestion, either in Departments of Civil and Environmental Engineering or in Departments of Agricultural and Bio-Systems Engineering. We did not conduct an exhaustive search of universities nor did we rank the importance or value of the research conducted. Following is a list of individuals and universities who are known to do this research:

Jennifer Aurandt, Ph.D.
Assistant Professor of Chemistry/Biochemistry
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Flint, Michigan

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University of Michigan
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Steve Safferman, Ph.D.
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David Stensel, Ph.D.
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Daniel H. Zitomer, Ph.D., P.E.
Department of Civil and Environmental Engineering
Marquette University
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Additional universities doing research for the U.S. EPA AgStar program on Anaerobic Digestion.

- Biogas and Anaerobic Digestion Program at Penn State University
- Department of Agricultural and Bio-Engineering at Purdue University
- Department of Agricultural and Biosystems Engineering at North Dakota State University
- Department of Biological and Agricultural Engineering at Texas A&M
- Department of Biological and Environmental Engineering at Cornell
- Department of Biological Systems Engineering at Virginia Tech
- Department of Bioproducts and Biosystems Engineering at University of Minnesota
- Department of Biosystems and Agricultural Engineering at Oklahoma State University
- Department of Civil and Environmental Engineering at Colorado State University
- Wisconsin Bioenergy Initiative at the University of Wisconsin-Madison

International Researchers and Technology Vendors

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Jules van Lier (http://citg.tudelft.nl/en/about-faculty/departments/watermanagement/sections/sanitary-engineering/staff/jules-van-lier/)
Grietje Zeeman (http://www.wewur.wur.nl/popups/vcard.aspx?id=ZEEMA001)

Vincent O'Flaherty (http://www.nuigalway.ie/microbiology/vincent_oflaherty.html)

Damien Batstone (http://www.awmc.uq.edu.au/index.html?page=68422)

B.2 Thermal Conversion Process Research

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B.3 Vermiculture Research

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B.4 Research into Stirling Engine Run with Biogas

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