Great Forest
SUSTAINABILITY SOLUTIONS

An Analysis of New and Emerging Food Waste Recycling Technologies and Opportunities for Application

P. Richard M. Cook
BMedSci (USYD), MSust (USYD)
Sustainability Consultant
Great Forest

Executive Summary:

A number of technologies are presently emerging and/or establishing themselves economically and environmentally as viable alternatives to the current practice of landfilling food waste. These technologies cater to the whole spectrum of food waste management opportunities, from small commercial establishments up to municipal sized operations. The technologies may be broken down into the three main categories of biological digestion, non-biological volume/weight reduction, and thermal processing. Within each category are a number of subcategories that are further investigated within this report and the most suitable applications identified.

To summate the findings, in consideration of a number of factors elaborated on within the report, aerobic digestion to water technology represents the greatest opportunity for food waste reduction at the lower end of the waste quantity spectrum. At the larger end of the quantity spectrum (municipal level), anaerobic digestion in conjunction with thermal hydrolysis technology represents the greatest opportunity to not only reduce the quantity of food waste going to landfill, but also utilize the waste as a resource to generate energy, electricity and also net financial returns.

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Biological Digestion

Anaerobic Digestion

Name of technology: Wet/Dry Anaerobic Digestion

Concept/Science behind it: The controlled decomposition of organic materials by microbes in the absence of oxygen, generating fertilizer solids, water and biogas (approximately 70% methane, 28% CO_2)[1,2].

Leading vendors: ArrowBio; Valorga; FEED Resource Recovery; Gaia Recycle; Vagron; Waste Recovery Systems, Inc.; Canada Composting; Ecocorp; Organic Waste Systems, Global Enviro.

Materials accepted (food types and compostable bags etc.): All organic materials, including paper and compostable bagging, except woody organics (timber, tree branches). In large plants additional sorting equipment (trommels, air- sifters) can be added to accept and separate all MSW [1].

The level of moisture content within the feedstock will influence which type of system (dry-feedstock oriented/ wet-feedstock oriented) that is applicable for each application [4]. Wet-feedstock contains <15% total solids within a watery sludge mix, whilst dry-feedstock contains >15% total solids in a solid mass. The wet process requires a product with minimal contamination and a low tolerance for impurities, making presorting essential and the process unsuitable for usage in a number of contaminated applications. In comparison, the dry process is far more robust and can be utilized to process a variety of food waste products, even with contaminants present (sand, fibers, large particles)[3].

Output or end product and uses for said end product: Biogas (approximately 70% methane) that is used to power the whole operation with excess energy sold off to the grid; organic solids/sludge> 'digestate' that can be processed for fertilizer or compost; and waste-water (effluent), which may require further treatment before release back into the water stream depending on contamination levels[1,4].

Does end product or uses vary depending on input?: Yes, the greater the level of putrescible materials within the feedstock, the greater the amount of biogas produced. Higher proportions of sugary organics (fruits and vegetables), will further speed up the digestion process [5].

Onsite logistic requirements:

- **Footprint of unit-** varies depending on capacity of machine> 50lb/day at approx. 1m^3 to 150 ton/day at approx. 4 acres [6,7].
- **Electricity requirements-** no external electricity required- biogas produced by the digester can power system with surplus electricity/biogas for on- selling
- **Ongoing maintenance/up keeping/cleaning-** regular processing of digestate material is required; in smaller units, removal; in larger units, transportation to composting or processing facilities.
- **Capacity-** 66lb/day in-situ units to 150 ton+/day industrial units
- **Ease of operation-** smaller in-situ units are self automating, larger industrial units are very complex and require a large staff (>20 employees) to operate
- **Can new material continually be added or is there a delay-** Depends on the complexity of the system, cheaper systems have a time delay, more expensive systems can be continually

added to. Full digestion times are generally around 20 days but can be as low as 48 hours in smaller automated systems, and up to 80 days in larger units processing dense materials.

Upfront costs

- **Buy/lease options-** Unit price of small modular system>$20,000 [8]; capital costs of $110-$150/ton capacity for industrial systems [9].
- **Included maintenance or ongoing costs-** Regular maintenance required on all machines; costs associated with removal of digestate material from smaller machines.

Applicability of technology (where/who is using these already, what is success?: Although there are over 100 industrial digesters processing food waste in Europe, fewer than ten are currently operating in the United States [9]. Kroger has opened a 55,000-ton/year anaerobic digestion food waste to biogas facility to power its grocery store distribution center in Compton, California [10].
Overall the technology is very versatile and can be adapted to almost any food waste application. A variety of studies recommend anaerobic digestion as the most viable and economically feasible technology opportunity for large-scale food waste disposal in NYC [11].

Type and scale of applications (university, hotels, residential, office buildings (size of building), malls, restaurants, municipalities, etc.): Application varies depending on size of the machine. Since the general premise remains the same regardless of size, machines can range from modular household and restaurant systems with between 66lbs-2 tons/day of processing space through to industrial systems capable of processing several hundred tons per day [12]. Other systems use in-sink food grinding technologies to divert food waste to storage tanks for removal and treatment off site at facilities, requiring minimal tank storage space on-site [13].

Name of technology: Thermal Hydrolysis

Concept/Science behind it: A two-stage process involving high-pressure boiling of waste followed by rapid decompression. The waste sludge is then digested anaerobically by bacteria, producing high yields of biogas. The high-pressure boiling and rapid decompression act to break down the food waste into short chain fragments [14], which are subsequently digested by bacteria at a rate 200% faster than without the hydrolysis process [15]. Additionally, thermal hydrolysis pretreatment produces approximately 50% increased quantities of biogas (predominantly CH_4 and CO_2) over conventional anaerobic digestion. The high temperatures reached act to sterilize the sludge, making the output liquid waste and solid residue (approximately 10% of inputs) safe for use as compost additives. Overall the process has been identified to increase the net profitability of anaerobic digestion operations by around 40% [15].

In essence, thermal hydrolysis acts to use heat and pressure to partially break down the food waste for the bacteria into more manageable pieces, skipping one of the key rate limiting steps in the process of anaerobic digestion, speeding up the overall process and enhancing the quantity and efficiency of biogas production.

Leading vendors: Cambi, BioTHELys (owned by Veolia).

Materials accepted (food types and compostable bags etc.): All types of organic and food waste, including animal carcasses. Not suitable for plastic products. Natural fiber compostable bags are acceptable.

Output or end product and uses for said end product: Biogas (CH_4 and CO_2), used for electricity generation and as a fuel source; nutrient-rich liquid effluent which can be used as a fertilizer; and a solid compostable residue, which can be used as a compost and soil additive.

Does end product or uses vary depending on input?: No, the end products are always biogas; nutrient rich, liquid effluent; and the solid, compostable residue, yet the quantities of biogas produced will vary depending on the feedstock used.

Onsite logistic requirements:

- **Footprint of unit-** the plant must be located in proximity to an anaerobic digestion facility and will require an additional 0.5-2 acres of land, depending on scale of plant
- **Electricity requirements-** the biogas produced can be used as an energy source to completely power the operation, with significant quantities of surplus biogas, which can be on sold as an energy or electricity source.
- **Ongoing maintenance/up keeping/cleaning-** similar to a large anaerobic digestion facility, the plant requires a dedicated team to operate and maintain it (100ton/day plant requires 5 workers) [16].
- **Capacity-** the technology is scalable and can be implemented in all sizes of anaerobic digestion facility, from 5ton/day operations to >150ton/day operations.
- **Ease of operation-** Similar to an anaerobic facility, requires a trained, professional staff to operate the machine (100ton/day plant requires 5 workers) [16].
- **Can new material continually be added or is there a delay-** material must be added in batches due to the high pressures required for the process, yet batches can be large (many tons, depending on scale of plant) and the hydrolysis process is completed within several hours.

Upfront costs

- **Buy/lease options-** a 100ton/day plant will have capital costs of around $60/ton annual capacity, yet net profitability associated with operations will recoup costs within 5-7 years of operation.
- **Included maintenance or ongoing costs-** regular maintenance is required, as with all large machines, yet the relatively low complexity of the operation makes maintenance procedures straight-forward (cleaning, replacement of worn parts etc.)

Applicability of technology (where/who is using these already, what is success?: the technology is applicable in all applications of anaerobic digestion larger than 5ton/day. The technology is currently used to process sewerage waste, in association with anaerobic digestion facilities. A number of facilities are operating around the world, the largest being the 130,000tons/year plant in Blue Plain, Washington DC. The technology is widespread throughout the UK and Europe, yet although showing proven ability and economic returns, is still underutilized within the United States.

Type and scale of applications (university, hotels, residential, office buildings (size of building), malls, restaurants, municipalities, etc.): due to the greatest economic returns being associated with large economies of scale operations, the technology is most suitable at a municipal level.

Aerobic Digestion

Name of technology: Food Waste to Water

Concept/Science behind it: Food waste is broken down aerobically (in the presence of oxygen) by natural organic bacteria, producing nutrient-neutral grey water, disposed of through the sewer [17].

Leading vendors: BioHitech America, EnviroPure Systems, Totally Green, Power Knot LLC, Waste to Water, Food2Water.

Materials accepted (food types and compostable bags etc.): Only food waste, not compostable bags. Food exclusions include: large bones, mussel and clamshells, pineapple tops, cornhusks and raw bread dough [17]. A shredder can be equipped on some brands to process everything except the raw bread dough [18] (yeast microbes in dough would destroy the unit's bacteria colonies.)

Output or end product and uses for said end product: Nutrient rich wastewater, discharged to the sewer system.

Does end product or uses vary depending on input?: No, the end product will always be water, as long as appropriate feed stocks are added. The feedstock may influence the level of biochemical oxygen demand (BOD) within the wastewater, which is regulated by municipal wastewater treatment plants. Foods such as diary or dough have inherently higher BOD levels.

Onsite logistic requirements:

- **Footprint of unit-** 800 lbs/day – 1.2yds^2; 2500 lbs/day – 2yds^2.
- **Electricity requirements-** 208 Volt 3-phase power.
- **Ongoing maintenance/up keeping/cleaning-** adding of new bacteria every 2-12 months depending on brand (very easy).
- **Capacity-** up to 2,500 lbs/day of processing to water capacity.
- **Ease of operation-** extremely easy, self automated.
- **Can new material continually be added or is there a delay-** yes, new material can be continually added to the system.

Upfront costs

- **Buy/lease options-** can be bought up-front for around $20,000+, or rented on a monthly basis, including maintenance and upkeep costs.
- **Included maintenance or ongoing costs-** included in price for rental units or as an option for fully purchased units.

Applicability of technology (where/who is using these already, what is success?: More than a dozen US vendors, the technology is already being utilized by a number of hotel organizations including the Hyatt organization; the Waldorf Astoria in NYC and the La Costs Resort and Spa, CA[19]. The technology has been proven very successful within commercial applications and is ready for mass distribution. *Independent tests have revealed that levels of BOD may exceed some municipal wastewater standards and therefore checking should be done before recommending the technology [8].*

Type and scale of applications (university, hotels, residential, office buildings (size of building), malls, restaurants, municipalities, etc.): The technology and range of sizes available holds opportunities for application within almost all small to medium sized establishments generating food waste as long as they have plumbing infrastructure to connect the machine to. The technology is proven and represents an excellent opportunity to reduce an organization's food wastage and the associated environmental and economic impacts.

Name of technology: Food Waste to 'Compost' (solids)

Important to note: although marketed as the end product being compost, independent test have shown that the solid organic end-product is not sufficiently biologically stable to be considered as compost and therefore requires further composting before being used as a compost > better considered as a 'composting additive.'

Concept/Science behind it: Food waste is broken down aerobically (in the presence of oxygen) by natural organic bacteria, producing a nutrient rich organic solid that can be composted to produce fertilizer.

Leading vendors: EnviroPure Systems.

Materials accepted (food types and compostable bags etc.): Only food waste, including compostable bags. Food exclusions include: large bones, mussel and clamshells, pineapple tops, cornhusks and raw bread dough [17]. A shredder can be equipped to process everything except the raw bread dough [18] (yeast bacteria in dough would destroy the unit's bacteria colonies).

Output or end product and uses for said end product: Nutrient rich bio-solid ready for composting.

Does end product or uses vary depending on input?: No, the end product will always be compostable bio-solid, as long as appropriate feed stocks are added.

Onsite logistic requirements:

- **Footprint of unit-** 800 lbs/day – 1.2yds^2; 2200 lbs/day – 2yds^2.
- **Electricity requirements-** 208 Volt 3-phase power.
- **Ongoing maintenance/up keeping/cleaning-** adding of new bacteria every 2 months (very easy)
- **Capacity-** 220 lbs/day up to 2,200 lbs/day of processing to water capacity
- **Ease of operation-** extremely easy, self automated.
- **Can new material continually be added or is there a delay-** yes, new material can be continually added to the system.

Upfront costs

- **Buy/lease options-** can be bought up-front for around $15,000+, or rented on a monthly basis, including maintenance and upkeep costs.
- **Included maintenance or ongoing costs-** included in price for rental units or as an option for fully purchased units.

Applicability of technology (where/who is using these already, what is success?: The technology has been proven successful in the digestion of food waste to a nutrient-rich biosolid, yet is limited in its applicability due to the greater capabilities of the food waste to water processing models. As such, the technology is only more effective in applications when water supply is limited and/or sewer access for waste is not practical.

Type and scale of applications (university, hotels, residential, office buildings (size of building), malls, restaurants, municipalities, etc.): The technology and range of sizes available holds opportunities for application within almost all small to medium sized establishments generating food waste that do not have effective potable water/sewer access. The technology is proven and represents an excellent opportunity to reduce an organization's food wastage and the associated environmental and economic impacts.

Non-biological Volume/Weight Reduction (Mechanical Processing)

Name of technology: Food Waste Pulpers and Shredders

Concept/Science behind it: Mechanical blades grind or shred the waste in the presence of water to create a pulp, which is then pressed to remove the majority of the water content. Volume/weight reductions are in the vicinity of 80-90%, depending on composition of feedstock [8].

Leading vendors: JWC Environmental, Untha UK, InSinkErator, Somat, Zago Green Division, Hobart Corp., NA Trading House.

Materials accepted (food types and compostable bags etc.): All food waste, no compostable bags as they can clog the grinding mechanisms. Additionally, paper, tinfoil, cardboard and plastic products such as flatware and Styrofoam can also be added, although doing so will contaminate the output and negate the opportunity for utilizing the output as compost feedstock.

Output or end product and uses for said end product: 80%**=** grey-water which can be disposed of in sewer or used as irrigation water, 20% semi-wet pulp which may be used as a compost feedstock depending on plastic contamination levels or alternatively disposed of in landfill.

Does end product or uses vary depending on input?: Yes, as mentioned, uses for semi-wet pulp vary depending on plastic contamination levels.

Onsite logistic requirements:

- **Footprint of unit-** 400lbs/hour capacity- 8sqft; 1000lbs/hour capacity- 12sqft.
- **Electricity requirements-** runs off standard mains power, larger machines requiring 3-phase. Electricity costs vary depending on machine capacity but approximately $7-10 per day electricity costs.
- **Ongoing maintenance/up keeping/cleaning-** regular (daily) cleaning is required, yet cleaning procedure is very simple with minimal time consumption.
- **Capacity-** range of capacities from 100lbs/hour up to >1500lbs/hour
- **Ease of operation-** very easy to use: turn on machine, insert food waste, and collect semi-dried material.

- **Can new material continually be added or is there a delay-** yes new material can be continuously added to the system.

Upfront costs

- **Buy/lease options-** 100lb/hour capacity- $1000 upwards; 1000lb/hour capacity- $15000 upwards.
- **Included maintenance or ongoing costs-** depends of model, 2-year parts and service warranty in common in good brands (eg: InSinkErator).

Applicability of technology (where/who is using these already, what is success?: The technology is well established and has been used in commercial and domestic applications for many years. Success rates are high and the comparative low complexity of the system makes maintenance requirements minimal.

Type and scale of applications (university, hotels, residential, office buildings (size of building), malls, restaurants, municipalities, etc.): The reliability of the technology, in addition to the range of capacities available, makes it suitable for almost all commercial kitchen applications. The under-sink capabilities of the technology require minimal space and effectively reduce the volume of food being subsequently disposed of. Advances in the technology of food dehydration and/or aerobic digestion pose further opportunities to couple the shredding/pulping system with such a unit to significantly reduce the volume and weight of food waste being disposed even further.

Interesting to note, Global Enviro offers products that work as a hybrid mechanical processing unit, dehydrator, and dry aerobic digester in one, acting to grind the waste and separate out the water before aerobically digesting the remaining solids to a garden safe, organic compost product [20].

Name of technology: Food Waste Dehydration

Concept/Science behind it: The food waste is added to the machine, which applies heat and agitation to evaporate the moisture out. The moisture is then collected and disposed of via the sewer and the remaining dried pulp (around 20% of volume/mass of original food waste) is removed and disposed of via landfill, as a feedstock for composting operations, or potentially as an ingredient in animal feed and soil fertilizers, subject to government regulatory approval [21].

Leading vendors: GaiaRecycle, Somat, EcoVim, Owareco, Hungry Giant, Food Cycle Science.

Materials accepted (food types and compostable bags etc.): Can process all food waste products, (although with minimal effectiveness of animal bones), and additionally soiled paper, waxed cardboard and napkins [22].

Output or end product and uses for said end product: Water (purity varies between models but generally classed as grey water for landscape watering or sewer disposal) and dried, odorless pulp.

Does end product or uses vary depending on input?: No, as long as appropriate feedstocks are added, end products will always be water (approximately 80%) and dried pulp (approximately 20%).

Onsite logistic requirements:

- **Footprint of unit-** 250 lbs/day – 1yd^2; 2500 lbs/day – 4.5yds^2.
- **Electricity requirements-** 220 Volt 3-phase power >> $4-$12 per cycle (depending on model size and feedstock volume/mass) [23]. Electricity intensive as no opportunity to regenerate power from feedstock.
- **Ongoing maintenance/up keeping/cleaning-** regular cleaning and up keep required- must collect the dried pulp produced after every cycle and wipe machine seals down (easy). Reports of machines requiring regular servicing due to technical problems have been common.
- **Capacity-** models range from 125lbs/day up to 3500lbs/day.
- **Ease of operation-** Very easy to operate, insert feedstocks and push a few buttons then collect end products.
- **Can new material continually be added or is there a delay-** in the most expensive systems, material can be added continuously, but in the majority of systems, batch loading is required. Turnaround times in batch loading models are around 6-24 hours.

Upfront costs

- **Buy/lease options-** Can be bought up-front for around $20,000+, or rented on a monthly basis, including maintenance and upkeep costs.
- **Included maintenance or ongoing costs-** Most contracts include maintenance for a fixed period of time; all rental contracts include service and maintenance as required at no extra cost.

Applicability of technology (where/who is using these already, what is success?: The technology is already in use by a variety of organizations, and has proved overall to be successful. It is important to note that there have been a number of cases where regular servicing has been required to fix problems with the machines of various brands, suggesting that there are still some slight limitations in reliability. Organizations already using dehydration technology include Rand Whitney Recycling, Montville, CT; St. Cloud Hospital, St. Cloud, MA; and Costo outlets nationwide.

Type and scale of applications (university, hotels, residential, office buildings (size of building), malls, restaurants, municipalities, etc.): Similar to aerobic digestion, the technology and range of sizes available hold opportunities for application within almost all small to medium sized establishments generating food waste. Although reliability issues are still being encountered in some applications, the technology is proven and represents an excellent opportunity to reduce an organization's food wastage and the associated environmental and economic impacts.

Thermal Processing

Name of technology: Waste to Energy Incineration

Concept/Science behind it: Combustion of MSW and capture of residual heat to generate electricity and heat via steam boilers [24].

Leading vendors: Beltran Technologies, NY; Continental Blower, LLC. NY; Hitemp Technology Corp. NJ; Envitech, CA; Enders-Process Equipment Corp. IL; Pennram Diversified Manufacturing Corporation, PA; International Waste Industries, MD; Thermcat technology corp. NJ.

Materials accepted (food types and compostable bags etc.): All food types and bagging (all MSW), ideally separated from metals etc. yet not essential (metals can be recollected from ash outputs).

Output or end product and uses for said end product: Energy (approximately 500-600 kWh/ton of MSW) and ash (approximately 15-20% of MSW by weight, 85% of which can be used in road construction, the remainder requiring land filling), with potential for collection and recycling of ferrous and non-ferrous metals[4].

Does end product or uses vary depending on input?: No, ash output remains constant, but with potential slight changes in energy harvested depending on feedstock.

Onsite logistic requirements:

- **Footprint of unit-** plant requires several acres of land, ideally located in close proximity to, but separate from, municipalities.
- **Electricity requirements-** nil, energy positive [24].
- **Ongoing maintenance/up keeping/cleaning-** requires regular cleaning and maintenance from a dedicated staff.
- **Capacity-** Average plant- 500-3000 tons of MSW per day
- **Ease of operation-** Complex- industry scale plant requiring trained operating staff.
- **Can new material continually be added or is there a delay-** yes, continuous adding [24].

Upfront costs

- **Buy/lease options-** Approximately $650/ton of annual capacity, requires long term MSW and energy contracts to be viable [24]. Can be worked to return profitability if located close to MSW source, minimizing transportation costs.
- **Included maintenance or ongoing costs-** Requires around 50 staff to operate. Regular ongoing costs associated with operation, cleaning and ash removal, yet can be worked to run profitably.

Applicability of technology (where/who is using these already, what is success?: Technology used worldwide, including Europe and Japan with almost 100 facilities operating in the United States. Facility operating in Newark, New Jersey processes 2800 tons of MSW/day producing 65MW of electricity for sale [23,24].

Type and scale of applications (university, hotels, residential, office buildings (size of building), malls, restaurants, municipalities, etc.): Suitable for municipalities, especially if it can be located in close proximity to a city and as such reduce waste transport costs and supply co-gen (electricity and heat) back to municipality.

Name of technology: Pyrolysis

Concept/Science behind it: Pyrolysis is the thermo-chemical decomposition of organic material at elevated temperatures in the absence of oxygen. The process involves the simultaneous change of chemical composition and physical phase, producing flammable syngas (CO & H_2), liquids (predominately crude oils), and high carbon content 'char' [25].

Leading vendors: International Environmental Solutions, Oneida Tribe, JBI, Vadxx, Greenlight Energy Solutions, Interstate Waste Technologies, GEM America.

Materials accepted (food types and compostable bags etc.): All organic wastes, the process is also particularly effective for plastic products [25]. *Not effective for metal inputs.*

Output or end product and uses for said end product: The nature of the inputs (petrochemical based versus organic waste based) will influence the composition of the end products. Organic and MSW based inputs will generate predominately syngas, whilst plastic based waste will generate a predominately crude oil based output [25].

Does end product or uses vary depending on input?: Yes, substantially, the required input will significantly influence the end products in terms of composition of the basic three elements of gas, oily liquids and char. The composition of inputs will similarly affect the methodology of pyrolysis undertaken (thermal pyrolysis or catalytic pyrolysis).

Onsite logistic requirements:

- **Footprint of unit-** 30 ton/day units require around 1000 ft^2 of land, plus processing space. Technology can be scaled up or down- a 3000 ton/day plant (capable of processing 25% of NYC's MSW requires around 20 acres of land [24].
- **Electricity requirements-** Electricity intensive, requires around 480kWh/ton of plastic waste [25], yet generates sufficient syngas and/or crude oil to be rendered energy positive in most applications.
- **Ongoing maintenance/up keeping/cleaning-** requires regular maintenance and cleaning by dedicated plant staff.
- **Capacity-** technology is scalable- 30 ton/day units are commercially viable, and larger 3000 ton/day plants have been proven commercially feasible and viable.
- **Ease of operation-** complex- requires a dedicated staff of technicians with training in pyrolysis machinery operation.
- **Can new material continually be added or is there a delay-** depends on the technology being used, but generally material is added in batches.

Upfront costs

- **Buy/lease options-** Costs for plant development and operation of around $17-$60/ton of capacity, including electricity purchasing requirements. For a large 3000-ton/day facility, capital costs are approximately $600 million.
- **Included maintenance or ongoing costs-** Requires purchase of grid based electricity and natural gas to supplement energy requirements, yet returns net positive levels of syngas and/or crude oil.

Overall, after on-selling of the syngas and/or crude oil outputs, the pyrolysis process has been found to be very economically viable, generating around $275/ton of pyrolysis of plastic products [25]. Data for pyrolysis of MSW is not yet available yet can be expected to generate significantly less returns, approximately in the range of around $125/ton of MSW.

Applicability of technology (where/who is using these already, what is success?: Pyrolysis technology has currently only been proven as commercially feasible for recycling of plastics, which do not require pre-sorting or pre-cleaning [25]. Opportunities for food waste disposal are still being tested yet the technology holds promise for future applications (undergoing large-scale testing to ensure commercial viability for food waste disposal at this point in time).

Type and scale of applications (university, hotels, residential, office buildings (size of building), malls, restaurants, municipalities, etc.): The technology could most effectively be used at the municipality level, offering processing of a significant proportion of the MSW stream, in conjunction with separately recycled or co-mingled plastics. The nature of the outputs (syngas and crude oil) means that the greatest financial benefits would be gained via larger operations and associated economies of scale. Alternatively, the scalability of the technology would also make it feasible for slightly smaller applications such as universities and malls generating a significant amount of food and plastic waste products, yet the financial returns may not recoup the capital and operation costs.

Name of technology: Gasification

Concept/Science behind it: The conversion of carbon based materials (organic wastes and fossil fuel derived products) into CO, H_2 and CO_2. The materials are heated at high temperatures (>700°C) in an environment with insufficient oxygen to promote combustion. The high heat without burning causes the waste to break down, releasing syngas (CO, H_2 and CO_2) [26].

Leading vendors: Air Products, Ze-gen, Covanta, PyroGenesis Canada Inc., Westinghouse Plasma Corp., Alter NRG, ENTECH Renewable Energy Systems, PrimeEnergy.

Materials accepted (food types and compostable bags etc.): almost all MSW materials, including aluminium, but excluding other metal types.

Output or end product and uses for said end product: Syngas (combination of CO, H_2 and CO_2), and ash or slag. Ash and slag may be reutilized in a variety of applications including as a road base additive or within building bricks and architectural tiles [26]. In some applications, the levels of pollutants and contaminants within the ash/slag produced are excessively high and land filling is required [26].

Does end product or uses vary depending on input?: The primary end product remains constant – syngas, although the composition of the syngas (ratio of CO, H_2 and CO_2 will vary depending on feedstock and methodology used). As mentioned, the level of contaminants within the feedstock material will determine the usages available for the ash and slag produced.

Onsite logistic requirements:

- **Footprint of unit-** depends on the size of the unit, smaller systems (<1MW capacity) approximately 1 acre, larger systems (>1MW capacity) >3 acres
- **Electricity requirements-** depending on the technology utilized, the majority of plants are net electricity generators. Syngas outputs can be utilized as a power source on-site or sold to offset grid electricity costs.
- **Ongoing maintenance/up keeping/cleaning-** the nature of the process using a feedstock such as MSW generates a significant amount of tar resin and ash buildup, requiring regular cleaning of the reactor vessel and ventilation stack.
- **Capacity-** technology is scalable- 30 ton/day units are commercially viable, and larger 3000 ton/day plants have been proven commercially feasible and viable.
- **Ease of operation-** Complex- requires a dedicated staff of technicians with training in pyrolysis machinery operation.
- **Can new material continually be added or is there a delay-** there are different types of systems, smaller cheaper systems (<1MW capacity), known as 'Fixed-bed reactors' require

regulated in-feeding, whereas larger (>1MW capacity) 'Fluidized-bed reactors' allow for variable rate of input feed and mixed fuels [28].

Upfront costs

- **Buy/lease options-** 750 ton/day plant costs around $150 million in capital outlay [27]. On average, capital costs are approximately $520/ton/year.
- **Included maintenance or ongoing costs-** regular maintenance is required to clean the reactor and ventilation shafts of tar and ash buildup associated with the usage of MSW as a fuel source. Such maintenance may require several hours to one day of shutdown per 3-6 months [28].

Applicability of technology (where/who is using these already, what is success?:
Air Products is currently building a facility in Tees Valley in England, capable of generating 50MW of electricity from MSW producing electricity for 50,000 homes and diverting 350,000 tons of non-recyclable waste from landfill per year [29]. Covanta Energy Corp. currently operates a commercially viable 350-ton/day MSW gasification plant in New Jersey, which successfully operates with 95% availability[30].

Type and scale of applications (university, hotels, residential, office buildings (size of building), malls, restaurants, municipalities, etc.): Similar to pyrolysis, the technology could most effectively be used at the municipality level, offering processing of a significant proportion of the MSW stream. The scalability of the technology makes it feasible for slightly smaller applications such as universities and malls generating a significant amount of MSW, yet the financial returns may not recoup the high capital and operational costs in such applications.

Although the technology has been proven, tests are still being conducted at the commercial scale and as such, limited data is available on commercial viability. Indications are that the economic returns associated with the technology are excellent and may significantly outweigh other technologies available. Pyrolysis stands as the technology to watch for the near future [29].

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