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ESTIMATING THE ECONOMIC FEASIBILITY OF BIOSOLIDS TREATMENT BY SMOULDERING

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Abstract: Within wastewater treatment plants (WWTPs), approximately 50% of the operating expenses are associated with managing the solid by-product, biosolids, making it the most expensive component of the entire process. Managing biosolids is a major challenge, demanding complicated processing, expensive transportation, and wasteful disposal. The objective of this research is to investigate the economic feasibility of a new approach to managing biosolids that has potential to be more energy efficient and cost-effective than current disposal methods. Self-sustaining Treatment for Active Remediation applied ex-situ (STARx) was originally developed as a chemical waste management and soil-clean up technology. STARx is based on the concept of smouldering, a flameless form of combustion for solid and liquid fuels. Smouldering is thermally efficient, meaning the process can recycle much of the released reaction energy to destroy fuels containing little energy or significant moisture content (MC) that would otherwise not burn (e.g., via incineration). Previous research has demonstrated that up to 80% MC (wet mass basis) biosolids could be efficiently destroyed via smouldering. This is a key finding, as it suggests that this process can reduce the extensive processing (e.g., dewatering, thickening), which are significant WWTP expenditures. This research uses costs reported by the United States Environmental Protection Agency to estimate "target disposal costs" for retrofitting a STARx system into existing WWTPs that practice either land application or incineration. It was found that a target disposal cost within the range of $341-$823 per dry ton of biosolids is probably required to retrofit a wide range of WWTPs.

1 LITERATURE REVIEW AND PROBLEM STATEMENT

Municipal wastewater treatment plants (WWTPs) are energy intensive and operationally demanding public activities that require significant capital and infrastructure (Shannon et al. 2008). In the United States (U.S.), WWTPs and drinking water services account for 3-4% of all national energy consumption and 30-40% of the total energy consumed by municipalities, costing $4 billion/year (U.S. EPA 2018). The scenario is quite similar in Canada, as both countries experience similar per capita water usage in comparable economies and social norms. Furthermore, as much of North America's WWTP infrastructure approaches the end of its design life, an estimated $271 billion and $26 billion is required in the U.S. and Canada, respectively, to repair and upgrade WWTP infrastructure to fair working condition (CIRC 2016, ASCE 2017). These costs represent 1.4% and 1.5% of the U.S. and Canadian 2017 GDP, respectively (CIA 2018). It is important to note that these costs do not consider upgrades due to evolving regulations (e.g., those that could result from emerging contaminants).

This presents a significant financial burden for North American municipalities, which are already in debt. A 2007 survey conducted collaboratively by The Federation for Canadian Municipalities and McGill

University found that Canada's municipal deficit was $123 billion, where all water supply systems (i.e., drinking water, wastewater, and storm water) constituted 25% of the deficit (Mirza 2007). Optimistically, the resulting benefits from improved WWTP infrastructure are expected to greatly outweigh these costs. Environment Canada (2013) estimated that $5.5 billion was required for Canadian WWTPs over the next 54 years to meet established regulations ($3.0 billion for capital, $1.7 billion for operation and maintenance (O&M), and $0.75 billion for reporting and monitoring). These costs were anticipated to provide $16.5 billion in benefits estimated from numerous projections including increased land value, greater recreational use of water bodies, increased commercial fishing, and reduced water supply costs. In addition, these costs are probably conservative as many environmental and social benefits are extremely difficult to quantify and are often undervalued (Hanley et al. 1998). In another sense, poor WWTP infrastructure could cause insidious environmental damage, where the ramifications and costs from such damage are not well understood or included in most cost-benefit analyses (Abdalla et al. 1992). The above information considers WWTP infrastructure holistically to present justification for the advancement of WWTP technology. It is equally worthwhile to identify the operations that are currently driving the high costs. Generally, the highest costs in WWTPs are associated with biosolids management (Khiari et al. 2004).

Following technical documents on biosolids management from the U.S. Environmental Protection Agency (U.S. EPA), O&M and capital cost ranges for popular biosolids processing and disposal methods have been compiled (U.S. EPA 2000a-g, 2002, 2003a-c, 2006a-b). Table 1 summarizes the high and low ranges of O&M costs for various biosolids processing technologies, and costs for disposal via application or incineration.

Table 1: Estimated Biosolids Processing and Disposal Cost Ranges

Processing | Disposal	Cost Range (2018 USD /Dry Ton of Biosolids)	
	Low	High
Thickening	0.40	4.02
Dewatering	93	299
Polymer Addition	0.0	28.0
Stabilization	15	491
* Land Application	94	456
Incineration	106	341

* Land Application costs may be offset up to $20/ton by selling composted biosolids as fertilizer (U.S. EPA 2002), but these savings were neglected due to infrequent practice.

It is important to caution that these approximations may not accurately represent current technology as the technical documents were published from 2000 to 2006, with some cost information dating as far back as 1987 (U.S. EPA 2000d). However, this information is assumed sufficient to understand the relative cost differences between popular biosolids management technologies. All values have been converted to 2018 USD following historical U.S. inflation rates from The World Bank (2018). It is interesting to highlight the large variability in capital and O&M costs. For example, gravity thickening capital costs vary between $286 500 and $4.60 million, and alkaline stabilization O&M costs vary from $61 to $481 per dry ton of biosolids processed (U.S. EPA 2000a). These costs vary with WWTP scale, inflow conditions, local electricity rates, etc. (King and Painter 1986). Altogether, these costs provide the framework for estimating the economic feasibility for new biosolids management technologies. This is important in identifying target O&M costs and the types of WWTPs these new technologies would best fit into, from a financial perspective. For this study, these costs will be used to discuss the economic feasibility of a novel biosolids disposal technology: Self-sustaining Treatment for Active Remediation applied ex-situ (STARx).

STARx has been in research and development for over ten years and was initially conceived for brownfield soil clean-up and hazardous, organic liquid waste management (Switzer et al. 2009, Pironi et al. 2011, Switzer et al. 2014). Currently, STARx is being implemented as a simple, low cost remediation technology at multiple sites around the world (Scholes et al. 2015, Grant et al. 2016). STARx utilizes self-sustaining smouldering: a flameless form of combustion commonly observed as the glowing, surface reaction surrounding charcoal briquettes in a traditional barbecue (Ohlemiller 1985). By mixing the hazardous wastes into a solid, porous medium (e.g., a bed of sand), a smoulderable mixture can be formed. This is due to: (1) forming permeable pathways to deliver the air (oxidant) to the reaction zone, (2) increasing the surface area of the waste (fuel), and (3) mitigating the heat losses out of the system, thereby recycling energy released from the reaction within the sand bed. This facilitates a thermally efficient process that can destroy a wide range of organic wastes that otherwise face limited disposal options. Furthermore, as the process is self-sustaining, it only requires energy input for ignition, after which the reaction can continue indefinitely with a minimal supply of air. Recently, it was shown that human faeces up to 75% moisture content (MC, wet mass basis) could be robustly smouldered in a simple reactor (Yermán et al. 2015, Yermán et al. 2016, Fabris et al. 2017). This was developed for implementation in a low-cost, simple toilet for improving sanitation in developing countries. Rashwan et al. (2016) demonstrated that biosolids from WWTPs with up to 80% MC could also be successfully smouldered. This is an exciting result as it suggests that biosolids processing (e.g., dewatering and thickening), which require significant O&M costs, may be reduced prior to disposal using a smouldering system, which itself should require minimal O&M costs. This finding has led to the development of a scale-up project that follows the conditions investigated at the lab scale (0.0080 m^3), using reactors at two prototype scales (0.27, 2.4 m^3). This project is ongoing and aims to identify the key benefits and challenges with increasing scale, and better distinguish the operating conditions relevant to the full-scale design of a smouldering system for biosolids.

2 ECONOMIC FEASIBILITY ANALYSIS

An economic feasibility analysis was conducted to estimate the “target disposal costs” (in 2018 US dollars per dry ton of biosolids) required to retrofit eight hypothetical WWTPs under various operating conditions with a new STARx smouldering system for biosolids disposal. A STARx system’s O&M costs would need to be less than these target disposal costs to be an economical retrofit. The target disposal costs required for replacing land application or incineration were considered, as these are the most popular disposal methods practiced in Canada (Apedaile 2001).To estimate the target disposal costs, the current O&M costs required for land application and incineration must be understood. Furthermore, capital costs will not be considered, only O&M cost comparisons will be used to estimate the target disposal costs.

Each biosolids disposal option requires a specific sequence of biosolids processing steps, or “processing path”, to condition the biosolids prior to disposal. The biosolids processing paths assumed for land application, incineration, and STARx are summarized in Table 2. Land application requires some degree of stabilization to achieve either Class A or B biosolids for safe use and, depending on the desired biosolids MC, may also require rigorous thickening and dewatering with polymer addition (U.S. EPA 1995). Incineration does not usually require stabilization but does require dewatering and thickening (usually with polymer addition) to reach a final MC between 60-85% (U.S. EPA 2003b). As STARx only requires minimal biosolids processing, an economical processing path was chosen to condition the biosolids to 80% MC with a lower heating value greater than 1.6 kJ/g. These properties have been shown suitable for disposal via smouldering (Rashwan 2015). This processing path requires minimal biosolids dewatering and thickening, without polymer addition, where low-end processing costs are assumed sufficient (Table 2). Each processing step has a range of reported costs, and is influenced by many factors including: prior processing, influent characteristics, and plant size (Metcalf and Eddy 2003). For a given processing path, summing the lowest cost estimates for all steps provides a low-end estimate of the processing path cost, while summing the highest cost estimates provides a high-end estimate. Ranges also exist for estimates of the disposal costs, from which the highest and lowest reported values provide the end-points. Taken together, it is possible to define the envelope of expected costs, from the highest possible processing path/disposal costs (high/high), through intermediate cases (high/low, low/high) to the lowest possible processing path/disposal costs (low/low). The range of possibilities in combining processing path/disposal end-point costs is summarized in Table 2.

Table 2: Processing Pathways and Cost End-Points for Considered Disposal Options

Disposal	Expected Processing Path	Processing Path Cost Range	Disposal Cost Range
Land Application	Thickening, Polymer Addition, Stabilization, and Dewatering	High/Low	High/Low
Incineration	Thickening, Polymer Addition, and Dewatering	High/Low	High/Low
STARx	Minimal Thickening and Dewatering	Low	-

Table 3 presents the target disposal costs estimated to replace either incineration or land application with a STARx system in eight hypothetical WWTPs. These target disposal costs are estimated by comparing the expected processing path/disposal costs required for land application and incineration, to the low-cost biosolids processing path assumed for a STARx system (Table 2).

Table 3: STARx Target Disposal Costs for Replacing Incineration and Land Application

(2018 USD/Dry Ton of Biosolids)

PROCESSING PATH COST RANGE	DISPOSAL COST RANGE			
	High		*Low*	
	Incineration	Land Application	Incineration	Land Application
High	$579	$1 185	$344	$823
Low	$341	$471	$106	$109

Table 3 suggests that target disposal costs would vary greatly between WWTPs: from $106 per dry ton of biosolids to replace the most economical WWTP practicing incineration, to $1185 to replace the most expensive WWTP practicing land application. Moreover, replacing land application, which may require a target disposal cost between $109-$1185, may achieve greater financial reward than replacing incineration, which may require a target disposal cost between $106-$579. This mainly results from removing stabilization, which is generally quite expensive (Table 1). This suggests that STARx may be an attractive retrofit for a larger fraction of WWTPs practicing land application compared to WWTPs practicing incineration.

It is important to note that target disposal costs to retrofit the four WWTPs with extreme processing path/disposal costs (i.e., low/low and high/high) are probably least realistic. Presumably, high disposal costs would be incurred from minimally processed biosolids following a low-cost processing path, and vice versa. E.g., low-cost processing generally results in high MC biosolids that would require high transportation costs for land application or extra costs for supplemental fuel for incineration. Therefore, considering these combinations may exaggerate the range of target disposal costs. Instead, it may be more practical to highlight the target disposal costs to retrofit the four WWTPs with intermediate processing path/disposal costs (i.e., high/low and low/high). These target disposal costs vary much less: from $471-$823 and $341-$344 to replace land application and incineration, respectively. This suggests that, if a WWTP intends to retrofit with a new disposal technology that minimizes its biosolids processing path costs, that technology's target disposal cost will probably be near the high-end costs of current disposal practices, i.e., $456 and $341 for land application and incineration, respectively (Table 1).

Currently, STARx contaminated soil treatment system O&M costs can be as low as $25 to $50 per mixture ton, depending on the volume of soils to be treated and the timeframes for remediation. However, these soils do not require mixing with a solid, porous medium (as is the case for biosolids) since the contaminated soil is a smoulderable mixture. Therefore, the presented target disposal costs may be achievable if the biosolids/solid ratio is high and the biosolids processing requirements are low. It is important to note that, as STARx is a new technology, information on O&M costs are very limited.

3 CONCLUSION AND SUMMARY

As WWTPs across North America approach their design life, there is a strong need to retrofit existing WWTPs with low energy, economical technologies. Smouldering combustion represents a promising approach to biosolids disposal that has the potential to greatly reduce a WWTP's energy footprint and serve as an economical retrofit. From the analysis presented, the estimated target disposal cost for a new smouldering system would vary depending on the current WWTP operating conditions, probably between $341-$823 per dry ton of biosolids. Furthermore, WWTPs practicing land application may benefit from greater financial savings by retrofitting with a smouldering system than WWTPs practicing incineration. As the first experimental scale-up study for a biosolids smouldering system is ongoing, the operating conditions are expected to become better understood. This study is anticipated to clarify the degree of biosolids processing and mixture conditions required for disposal, and better approximate the expected O&M costs.

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