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Development of a Novel, Two-Step Process for Treating Municipal Biosolids for Beneficial Reuse

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ABSTRACT

Modern municipal sewage waste treatment plants use conventional mechanical and biological processes to reclaim wastewaters. This process has an overall effect of converting a water pollution problem into a solid waste disposal problem (sludges or biosolids). An estimated 10 million tons of biosolids, which require final disposal, are produced annually in the United States. Although numerous disposal options for biosolids are available, including land application, landfilling, and incineration, disposal costs have risen, partly because of increased federal and local environmental restrictions *(1)*. A novel, thermomechanical biosolids pretreatment process, which allows for a variety of potential value-added uses, was developed. This two-step process first employs thermal explosive decompression to inactivate or kill the microbial cells and viruses. This primary step also results in the rupture of a small amount of the microbial biomass and increases the intrinsic fluidity of the biosolids. The second step uses shear to effect a near-complete rupturing of the microbial biomass, and shears the nondigested organics, which increases the overall surface area. Pretreated biosolids may be subjected to a secondary anaerobic digestion process to produce additional fuel gas, and to provide for a high-quality, easily dewatered compost product. This novel biosolids pretreatment process was recently allowed a United States patent.

Index Entries: Sewage sludge; biosolids; thermal mechanical treatment; beneficial reuse.

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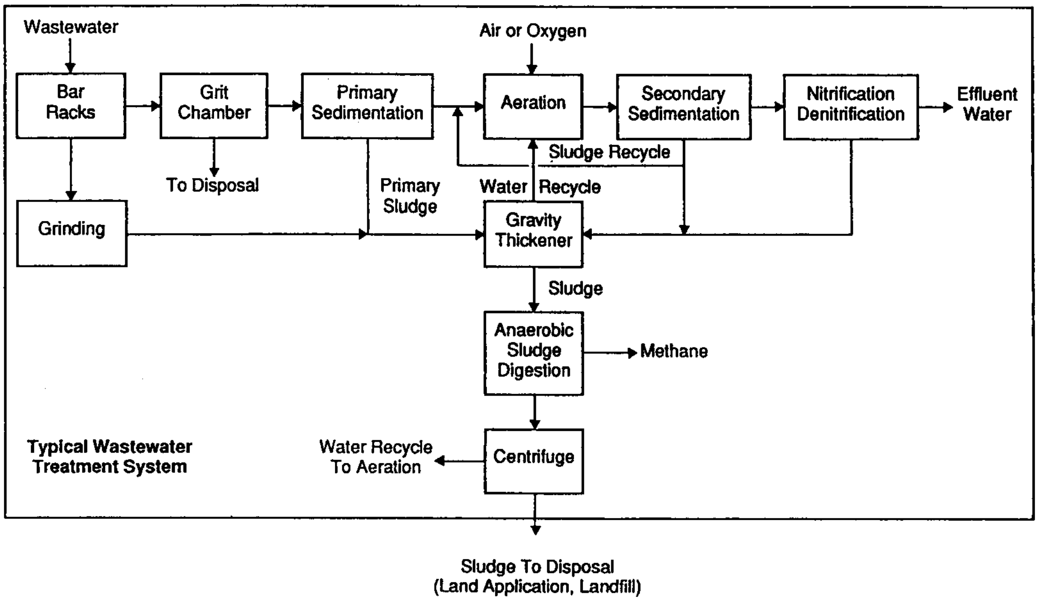

Fig. 1. Simplified process flow diagram for a conventional municipal sewage treatment plant.

INTRODUCTION

Conventional municipal sewage treatment plants use mechanical and biological processes to reclaim wastewaters (*see* Fig. 1). Disposing of microbial sludge solids that result from these treatment processes has historically been expensive, because of the extremely large volumes in which they are produced. These sludges contain high fractions of volatile solids (VS), they retain large amounts of water (70–85% before drying), and, because of the substantial bulk of the waste, the disposal costs are significant. Recently, the costs for disposing of sludges through conventional landfilling have risen dramatically, because of decreasing landfill availability. In some areas, microbial sludges are banned from landfills, because of the high pollution potential and the presence of active microbial catalysts, which further increase anaerobic bioconversion in the landfill.

An obvious solution to this disposal problem is to further reduce the organic content of the waste. This increases the potential for dewatering (reduction in bulk), and reduces both the pollution potential and pathogen load of the waste. Indeed, previous work by the authors shows that thermal mechanical pretreatment *(2)* effectively disrupts the macrostructure of municipal sewage sludges and renders them more amenable to secondary anaerobic bioconversion.

Although effective pretreatment was demonstrated for dilute sewage sludge, in commercial applications, sewage sludges are first dewatered to 15–30% total solids before final disposal. Therefore, pretreatment technology, which may effectively treat high-solids sludges, is required. The current study explores the use of a variety of thermal mechanical processes, such as those successfully used to pretreat biomass feedstocks before fermentation, to disrupt the macrostructure of highly dewatered sewage sludge for enhanced secondary anaerobic digestion.

MATERIALS AND METHODS

Sewage-Derived Sludge Procurement and Analysis

Municipal sewage sludge was obtained from the Denver Metropolitan Wastewater Reclamation District, Denver, CO. Dewatered sludge was collected from the belt conveyor after centrifugation, and was transferred to 40-gal plastic drums. The sludge was stored at 4°C in a cold room before use, in order to reduce unrelated breakdown of the material. The sludge was analyzed for a variety of important parameters, such as total solids, volatile solids, ash, total chemical oxygen demand (COD), soluble COD, and pH, as described previously *(3,4)*.

Pretreatment Technology

Highly dewatered municipal sewage sludges represent a solids handling problem with respect to the application of pretreatment technologies. Therefore, various thermal mechanical processes, which have been demonstrated as effective in pretreating biomass before being biologically converted, were reviewed. Pretreatments evaluated included thermal treatment, explosive decompression, and shear, either alone or in combinations. The technologies are described here in detail, and include a Parr cell disruption bomb, a masonite gun, and a conventional hydroheater. The Parr cell disruption bomb and masonite gun represent batch-operated systems; the hydroheater was operated in a continuous mode.

Parr Cell Disruption Bomb Experiments

Experiments were performed with a Parr (Moline, IL) model #4635 cell disruption bomb constructed of 316 stainless steel. It has an internal volume of 920 mL and is rated for a maximum working pressure of 2200 psig. The disruption bomb was outfitted with an adjustable pressure-relief valve (Nupro, Denver, CO, SS-4R3A1, with adjustable spring R3A-D, rated 1500–2250 psig) in place of the normal 3000 psig rupture disk provided by the manufacturer. The pressure-relief valve was calibrated for 2100 psig activation, so as not to exceed the 2200 psig working pressure rating of the vessel.

Treatment experiments were carried out by adding a 10-g sample to a 50-mL plastic beaker and placing it in the disruption bomb. Once the headplate was secured, a compressed-gas cylinder of either ultra-high purity (UHP) nitrogen, zero air, or carbon dioxide was attached via a quick-disconnect fitting. For some of the experiments, the bomb was placed in a temperature-controlled water bath and allowed to equilibrate for 1 h before being pressurized. Treatments that used nitrogen or air were carried out at 2000 psig; those that used carbon dioxide were carried out at 900 psig (greater pressures result in liquid carbon dioxide being added to the bomb). Pressure was administered to the bomb with a high-pressure needle valve. Periodically during the treatment, additional gas was administered to maintain the target pressure, because the gas would continuously dissolve in the sample. The experiments were pressurized for 3 h, then rapidly depressurized by opening a 0.5-in. ball valve on the headplate. The sample was then removed for immediate analysis of soluble COD.

Masonite Gun Experiments

Experiments were conducted using a laboratory-scale steam-explosion process previously developed in the laboratory of Estaban Chornet at the University of Sherbrooke (Sherbrooke, PQ, Can *[5]*). This system consisted of a batch-loaded, steam-jacketed reaction chamber and a ball valve, followed by two flash tanks to collect the product. Experiments were conducted by adding approx 500 g of sewage sludge or sewage sludge mixed with shredded municipal solid waste (MSW) to the reactor. After the headplate was attached, the sample was subjected to pressures of 100, 211, 322, or 471 psig by the addition of steam to the reaction chamber and jacket. After 4 min of reaction at the target pressure, the contents of the reactor were expelled to atmospheric pressure into the primary flash tank through a 1-in ball valve. A representative sample of the pretreated material was removed for immediate analysis of soluble COD.

Hydroheater Experiments

The hydroheater pretreatment system used a manual stainless steel hydroheater (series M103MSX by Hydro Thermal, Waukesha, WI) to perform high-pressure steam mixing. To feed high-solids sludges at high pressures to the hydroheater, a progressing cavity pump which allowed operation at sludge-feed pressures as high as 500 psig (Moyno, model 9JKS3, Robbins Myers, Springfield, OH) was used. System capacity was 0.1–5.0 gal/min of high-solids sludge. A high-pressure boiler system provided steam to the hydroheater (18 hp, gas-fired, model HB-H44605-THK, Vapor, Chicago, IL). Following treatment with high-pressure stream in the hydroheater, the sludge was flashed to atmospheric pressure in a 40-gal stainless steel tank. The system was stopped after being operated for approx 30 min, and representative samples from the primary flash tank were obtained for immediate analysis of soluble COD.

Additional experiments that used a treatment train were performed, in which sewage sludge was first treated as described above with the hydroheater system, followed immediately by shear treatment with the Ultra Turrax (IKa Works, Staufen, Germany, model T-45-S4) for 4 min at

50% power. After this treatment train was applied, representative samples were obtained for immediate analysis of soluble COD.

Determination of Pretreatment Effectiveness

In general, pretreatment effectiveness was evaluated based on release of soluble COD from the sewage-sludge sample. Briefly, 1 g of sample was diluted with 9 mL of dH_2O, and mixed vigorously. The diluted sample was placed into a 15-mL plastic centrifuge tube and centrifuged at 1000 rpm for 5 min at room temperature using a Sorval model GLC-4 centrifuge equipped with a H1000 rotor. A 100-μL sample of the upper phase (supernatant) was added to COD test vials (Hach, Loveland, CO, high-range plus). The COD assay was incubated for 2 h at 150°C, and read at 600 nm with a spectrophotometer (Milton-Roy, Rochester, NY, model 301). Increases in soluble COD are directly related to an increase in the anaerobic biodegradation potential of the organic sample *(2)*.

RESULTS AND DISCUSSION

Previous research identified the relative ineffectiveness of thermal, thermal–acid, thermal–alkaline, and enzymatic pretreatments in releasing soluble COD from low-solids microbial sludges *(2)*. Additional research identified optimum pretreatment of low-solids microbial sludges (1–3%) to require thermal and shear or sonication forces for efficient release of soluble COD *(2)*. These data were the basis for a US Patent (5380445 [1995]). However, industrial application dictates that the pretreatment technology be developed for high-solids sludges, and, if possible, in continuous mode. To this end, several approaches to high-solids sewage sludge pretreatment, including thermal treatment, explosive decompression, and shear, either alone or in combinations, were explored.

Analysis of the municipal sewage sludge obtained from the Denver Metropolitan Wastewater Reclamation Plant for this study is described in Table 1. Sludge analysis revealed a total solids content of slightly greater than 17%, and soluble COD that represented 4.9% of the total COD content.

Parr Explosive Decompression

Initial experiments that used either rapid decompression or rapid decompression with moderate thermal input are shown in Fig. 2 for microbial sewage sludge at 17.6% total solids. Compression gases included UHP nitrogen, carbon dioxide, and zero air. Data indicate that explosive decompression with nitrogen at 55°C releases the most soluble COD (17% release). Initially, the disappointing treatment effectiveness was attributed to slow gas penetration of the sludge sample, as a result of the total solids level. Therefore, experiments were also conducted with sewage sludge mixed with a processed MSW (50/50, w/w). The processed MSW consisted

Table 1
Analysis of Municipal Sewage Sludge Obtained from the Denver Metropolitan Wastewater Reclamation Plant

Parameter	Value
Total solids (TS)	17.3% ± 0.1
Volatile solids (VS, of dry wt)	66.5% ± 0.2
Ash (of dry wt)	33.5% ± 0.2
Total chemical oxygen demand (COD, mg/g wet wt)	187.5 ± 16.3
Soluble COD (mg/g wet wt)	9.2 ± 0.8
pH	8.01

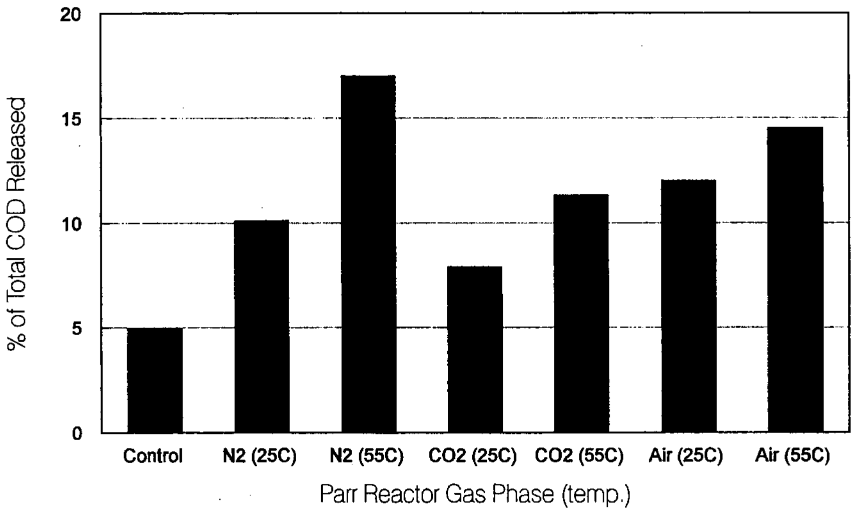

Fig. 2. Efficacy of explosive decompression using the Parr reactor on the release of COD from sewage sludge. The experiments were performed with sewage sludge alone at 17.3% total solids.

of the paper and packaging fraction of residential refuse shredded with an industrial-scale knife mill to pass a 1/4-in. screen. Mixing sewage sludge with processed MSW increased the total solids content to 48.6%, and enhanced the gas permissibility of the sludge. Data shown in Fig. 3 demonstrate only marginal increases in the effectiveness of pretreatment (~2%).

Masonite Gun Pretreatment

Steam-explosion pretreatment technology imparts thermal, explosive decompression and mild shear forces to the sample. Thermal treatment is first applied in a steam-jacketed reactor, then the sample is released rapidly through a relatively small orifice (imparting shear) during rapid decompression. Results indicate that maximum treatment effectiveness was

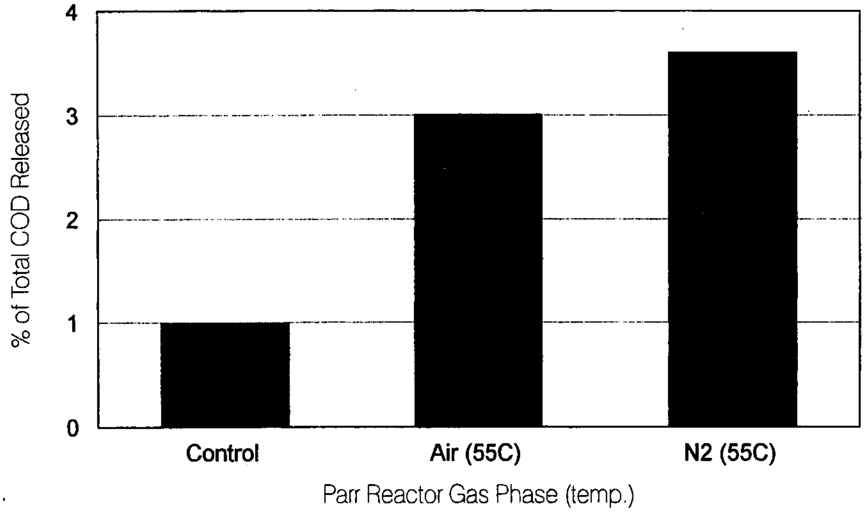

Fig. 3. Efficacy of explosive decompression using the Parr reactor on the release of COD from sewage sludge. Experiments were performed after blending sewage sludge and shredded MSW on a 50/50 weight basis. The sewage sludge and MSW blend was 48.6% total solids.

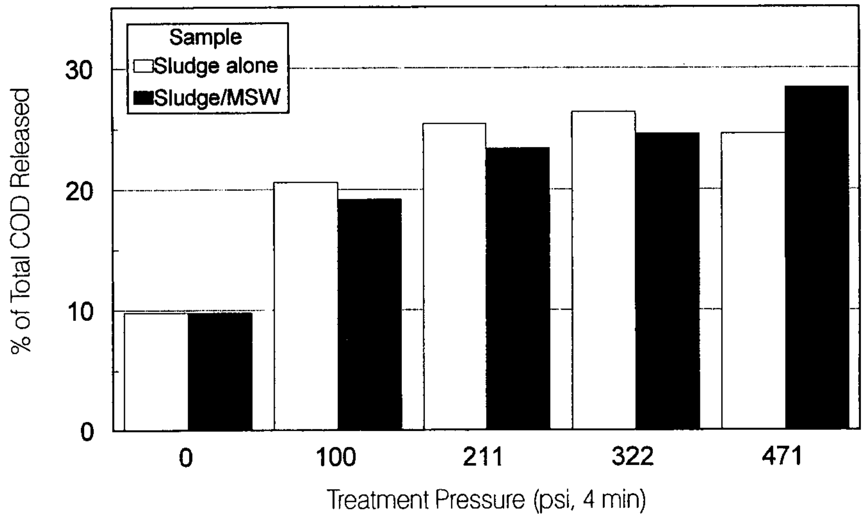

Fig. 4. Efficacy of explosive decompression using the Masonite gun system on the release of COD from sewage sludge.

achieved with operating pressures of 211–471 psi (Fig. 4). The maximum release of soluble COD by treating sewage sludge alone was ~25% at 322 psi. Additional experiments conducted with sewage sludge mixed with processed MSW (described earlier), to increase surface area for steam penetration, had little effect on the pretreatment results. The maximum treatment effectiveness was 27% COD release at 471 psi.

Table 2
Various Operational Parameters for Hydroheater System Operation

Run	Pressure (psi) Sludge pump	Pressure (psi) Steam[a]	Temperature (°F) Steam[b]	Temperature (°F) Hydroheater	Hydroheater sludge setting	Hydroheater mix rate[c]	Moyno pump controller[d] (Hz)
1	80–100	250	410 ± 8	285 ± 6	Medium	5	14
2	75–100	250	410 ± 8	293 ± 5	Medium	10	7
3	75–100	250	410 ± 8	265 ± 5	Medium	4	20
4	80–100	250	410 ± 8	265 ± 5	High	3	20

[a] Steam pressure was attenuated from the boiler system operated at 300 psi with a steam valve.
[b] Steam temperature is listed for a thermocouple probe installed immediately preceding the hydroheater.
[c] The hydroheater mixing rate was a function of a needle valve with 11 turns (0 = no steam addition).
[d] The moyno pump rate was adjusted with a Baldor series 15 inverter control. The percentage of full pump speed was determined as a function of the maximum Hertz rating of the motor (i.e., 60 Hz).

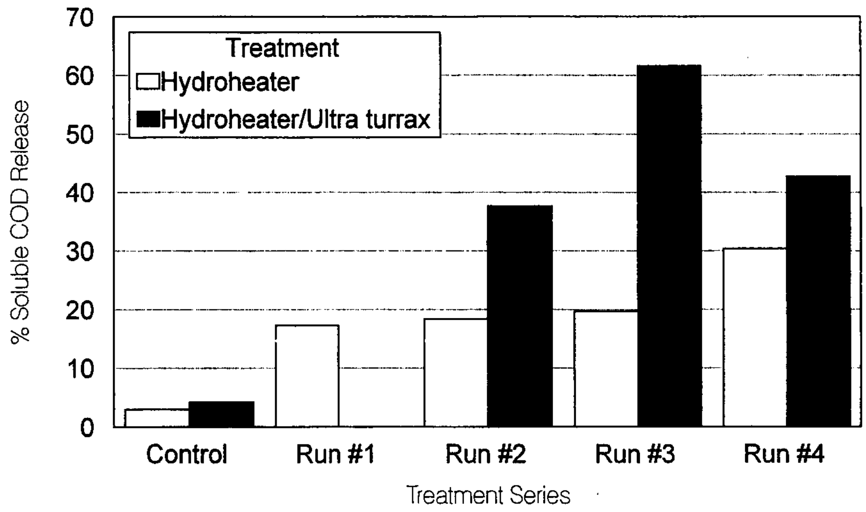

Fig. 5. Efficacy of explosive decompression using the hydroheater system on the release of COD from sewage sludge. Run conditions are as described in Table 2. For some experiments, a treatment train, including the use of shear (Ultra Turrax), was evaluated.

Hydroheater Pretreatment

Pretreatment that uses the hydroheater system is similar to steam explosion, because it imparts to the sample thermal, explosive decompression, and mild shear forces. However, the hydroheater system differs, because it represents a continuous (rather than batch) process. Several runs were conducted with the hydroheater system, with operational conditions as outlined in Table 2. Results using the hydroheater system alone demonstrate only a modest pretreatment effectiveness of 20–30% release of soluble COD (Fig. 5). However, a treatment train, which included a posttreatment with the Ultra Turrax, substantially increased soluble COD to 40–62%. Furthermore, additional experimentation may yield more improvements in treatment effectiveness. Greater than 80% release of soluble COD (similar to results obtained using low-solids pretreatment technology, [2]) may be possible.

Early analysis of energy requirements for pretreatment, compared to anticipated fuel gas yields for a secondary anaerobic digestion process, estimates the production of 237 BTU (net energy)/lb of sewage sludge treated (data not shown).

Data depicted in this paper formed the basis for a recently allowed US Patent.

ACKNOWLEDGMENTS

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