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Anaerobic Digestion of Municipal Solid Waste

Utility of Process Residues as a Soil Amendment

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ABSTRACT

Tuna processing wastes (sludges high in fat, oil, and grease [FOG]) and municipal solid waste (MSW) generated on Tutuila Island, American Samoa, represent an ongoing disposal challenge. The biological conversion of the organic fraction of these wastes to useful products, including methane and fertilizer-grade residue, through anaerobic high-solids digestion is currently in scale-up development. The suitability of the anaerobic digestion residues as a soil amendment was evaluated through extensive chemical analysis and greenhouse studies using corn as an indicator crop. Additionally, native Samoan soil was used to evaluate the specific application rates for the compost. Experiments established that anaerobic residues increase crop yields in direct proportion to increases in the application rate. Additionally, nutrient saturation was not demonstrated within the range of application rates evaluated for the Samoan soil. Beyond nutrient supplementation, organic residue amendment to Samoan soil imparts enhanced water- and nutrient-binding capacities.

Index Entries: Anaerobic digestion; tuna sludge; MSW; high solids; compost.

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INTRODUCTION

Disposal practices for municipal solid wastes generally involve conventional landfill operation. However, because of a critical storage of available land and cover materials on Tutuila Island, American Samoa, the landfill cannot be operated in the traditional "sanitary" method. Additionally, because of the lack of appropriate equipment and confined area, the landfill is not effectively compacted, resulting in an unstable area for refuse disposal vehicles.

Tuna canneries on Tutuila Island produce another major waste stream in the form of tuna sludge from processing operations. Presently, the tuna sludge is disposed of by ocean dumping under permit from the US Environmental Protection Agency (*1*). However, because of uncertain ocean currents and trade winds, shoreline contamination is possible. Previously, interruptions in the ocean disposal of tuna sludge have required shutdown of tuna-processing operations, thereby eliminating work for approx 37% of American Samoa's wage earners for a month at a time (*2*). Additionally, the cost is significant for ocean dumping of the large quantities of tuna sludge produced.

Biological conversion processes, such as anaerobic digestion, have been employed for centuries in disposing organic wastes, such as municipal sewage (*3–5*). Furthermore, the anaerobic digestion process can potentially generate two useful products—a fuel gas (methane) and a compost-quality soil amendment. Combining the MSW and tuna-sludge wastes and subjecting this feedstock to anaerobic bioconversion can therefore produce renewable fuel and quality topsoil on an island that lacks both.

This study evaluates the technical potential for using high-solids anaerobic digestion to convert a mixture of tuna sludge and MSW to fuel gas and anaerobic compost. The compost is evaluated in greenhouse studies using native Samoan soil, and with corn as an indicator crop to establish baseline data for use.

METHODS

Feedstocks

Tuna-processing wastes (sludge) were obtained from Pan Pacific Fisheries, Inc., Terminal Island, CA. During cannery operations, tuna-processing wastes are partially dewatered using dissolved air floatation (DAF) to produce a sludge for disposal. Tuna sludge from DAF was shipped frozen to our laboratory in Golden and maintained at $-20°C$ in freezers until use.

The MSW feedstock used in this study was obtained from Future Fuels, Inc., Thief River Falls, MN. The MSW was processed to remove glass, metals, plastics, and other nonbiodegradable materials using a combination of mechanical and manual separation as previously described (*6*).

Previous research on anaerobic bioconversion of MSW feedstocks identified the need for nutrient supplementation to ensure robust biological activity (*7*). For comparison purposes, fermentations were also performed using a combined MSW and nutrient solution as previously described (*7*).

Anaerobic Digester Operation

The laboratory-scale high-solids digesters used in this study were described previously (*8*). Each consists of a cylindrical glass vessel positioned with a horizontal axis and capped at each end. The agitator shaft runs horizontally along the axis of the cylinder, and mixing is achieved with a rod-type agitator (tines) attached to the shaft at 90° angles and in opposing orientation. Shaft rotation is provided by a low-speed, high-torque, hydraulic motor (Staffa, Inc., England). The glass vessel was modified with several ports, including two 3/4-in. ports for liquid introduction and gas removal and a 2-in. ball valve (Harrington Plastics, Denver, CO) for dry-feed introduction and effluent removal. The high-solids reactors were maintained at 37°C in a temperature-controlled warm room. The reactors were batch-fed daily by adding the relatively dry MSW feedstock and either tuna sludge or a liquid-nutrient solution. Sludge was removed from the reactors on a biweekly basis and stored at 4°C until analyzed.

Feedstock/Digester Effluent Analysis

Total solids (TS), volatile solids (VS), and ash were determined by differential weights following drying as previously described (*9*). Analysis of chemical oxygen demand (COD) employed the microdetermination method with commercially available "twist tube" assay vials (Bioscience, Inc., Bethlehem, PA) as previously described (*10*). Levels of volatile organic acids (C_2-C_5 iso- and normal acids) were determined by gas-liquid chromatography (GLC). A Hewlett-Packard Model 5840A gas chromatograph equipped with a flame ionization detector, a Model 7572A autosampler, and a Model 5840A integrator (all from Hewlett-Packard) were used. The chromatograph was equipped with a glass column packed with Supelco 60/80, Carbopack C/0.3%, Carbowax 20M/0.1% H_3PO_4 for separations.

Gas Analysis

Total biogas production in high-solids anaerobic digesters was determined using calibrated wet-tip gas meters (Reber Point Wet Tip Gas Meter Company, Nashville, TN). The composition of the biogas produced was determined by gas chromatography as previously described (*11*).

Theoretical Methane Yield

The theoretical methane yield for the combined feedstocks tested was calculated as previously described (*12*) from the feedstock COD content.

The ratio of the actual methane yield for a given anaerobic fermentation system to the theoretical methane yield calculated from the feedstock COD value directly reflects the organic carbon conversion of the added substrate.

Compost and Samoan Soil

The anaerobic compost used in plant-growth experiments was derived from laboratory-scale high-solids digesters. This material was dried to $<10\%$ moisture content using a high-capacity, woodchip tray dryer (Despatch Co., Minneapolis, MN). The compost material was analyzed both before and after drying.

A representative sample (600 kg) of soil from American Samoa was collected by American Samoa Community College staff and shipped to Colorado for use in plant-growth studies.

Chemical Analysis of Compost Materials and Samoan Soil

Anaerobic compost materials were analyzed for extractables and total-element composition, and soil was analyzed for texture, extractables, and total-element composition as described in the Colorado State University Soil Testing Laboratory Procedures Manual (*13*).

Greenhouse Plant-Growth Studies

Plant-growth studies were conducted using corn as an indicator crop because of its high nutrient requirements. The study used triplicate determinations for each compost amendment rate using a randomized complete block design. The soil was initially well mixed with or without compost amendment, separated into 4-kg quantities, and placed in plastic pots. The moisture content in the pots was maintained at field capacity by watering the plants daily using the gravimetric technique. Corn was grown for a 6-wk period prior to harvesting. At harvest, the corn shoots and roots were collected, washed, and oven-dried at 65°C for 72 h to obtain dry-matter and chemical measurements.

RESULTS

Because of the remote location of the tuna canneries in American Samoa, local (California) tuna sludge was procured for this study. The compositional characteristics of both tuna sludge and MSW are compared in Table 1. The data indicate a high moisture content for the tuna sludge as compared to the MSW, although both waste materials were substantially high in volatile-solids content. Analysis of feedstock polymer content revealed the tuna sludge was composed primarily of protein, fat, oil, and

Table 1
Compositional Analysis of Tuna Sludge and MSW Feedstocks

Parameter	Tuna sludge	MSW
Total solids (%)	11.3 ± 0.7	72.7 ± 1.8
Volatile solids (% of TS)	81.4 ± 1.4	87.5 ± 1.6
Ash (% of TS)	18.6 ± 1.4	12.5 ± 1.6
COD (mg/g wet wt)	213.7 ± 4.2	727.0 ± 4.7
Protein/fat/oil/grease (% of VS)	96.8 ± 0.3	16.4 ± 1.0
Hemicellulose (% of VS)	0.6 ± 0.3	4.4 ± 1.3
Cellulose (% of VS)	0.8 ± 0.1	62.5 ± 2.5
Lignin (% of VS)	4.1 ± 2.1	13.7 ± 1.2

Table 2
Analysis of High-Solids Anaerobic Conversion of Combined Feedstocks

Parameter	MSW/tuna sludge	MSW/nutrient solution
Organic loading rate (g VS/L·d)	14.1	14.1
Feedstock ratio (g VS/g VS)	2.4:1	19:1
Sludge pH	7.85 ± 0.11	7.70 ± 0.05
Sludge volatile fatty acid pools (mM)	32.3 ± 5.8	23.5 ± 1.2
Total biogas production (L/g VS·d)	0.698 ± 0.041	0.588 ± 0.030
Methane content (%)	63.7 ± 2.7	53.5 ± 2.0
Anaerobic conversion (%, based on combined feedstock COD content	84.6 ± 2.1	76.7 ± 1.8

grease, whereas the MSW contained predominately cellulose (owing to the high paper and packaging content).

High-solids anaerobic fermentation studies were conducted with laboratory-scale digester systems, and required a 3-mo period for adaption of the microbial consortium from a previous biomass feedstock to either the MSW/tuna sludge or MSW/nutrient solution feedstock. Following the initial adaptation period, the anaerobic fermentation data were collected for a 6-mo period of performance. The fermentation data as described in Table 2 demonstrate stable anaerobic bioconversion of both combined feedstocks through normal sludge pH and relatively low volatile fatty acid pools. The overall conversion of both combined feedstocks at relatively high organic loading rates (14 gVS/L·d) were quite high (>75%), consistent with past fermentation research on optimizing nutrient requirements for robust anaerobic conversion systems. The overall conversion of the MSW/tuna-sludge feedstock represents an approx 8% increase over that for complete nutrient supplementation of the fermentation

Table 3
Chemicals Analysis of Anaerobic Compost Samples

	MSW/tuna sludge		MSW/nutrient solution	
Parameter	Wet basis	Dry basis	Wet basis	Dry basis
Moisture (%)	79.8		78.9	
pH	7.80		7.60	
EC sat extract	16.40		17.2	
SAR	19.0		24.0	
Org. matter (%)	10.9	54.0	8.9	42.0
Org. carbon (%)	6.3	31.3	5.1	24.1
C/N	12.8	12.8	11.3	11.3
Nitrogen	0.49	2.43	0.45	2.13
Phosphorous	0.23	1.14	0.21	0.99
Potassium	0.14	0.69	0.14	0.66
Calcium	0.44	2.18	0.44	2.10
Magnesium	0.10	0.49	0.10	0.47
Sulfur	0.13	0.64	0.09	0.43
Iron	0.14	0.69	0.13	0.62
Sodium	0.07	0.37	0.07	0.38
mg/kg				
Manganese	40	200	40	200
Zinc	178	881	172	815
Copper	35	173	29	137
Boron	12	59	15	71
Molybdenum	1	6	1	5

represented by the MSW/nutrient-solution feedstock. Additionally, the methane content of the biogas derived from the anaerobic fermentation of the MSW/tuna-sludge feedstock is enhanced by almost 10% over that for the nutrient-supplemented MSW.

The anaerobic residues derived from high-solids fermentation experiments were dried for use in plant-growth studies. The analysis of this ''anaerobic compost'' is described in Table 3 and indicates that both composts are similar in available nutrients that may be adequate for plant growth. The electrical conductivity (EC) and the sodium adsorption ratio (SAR) are very high in both composts for plant growth. However, the negative effect of high salts is diluted after mixing the compost with soil. Comparisons of wet with dried compost indicate that the drying process resulted in a >90% loss in ammonia nitrogen, whereas the concentrations of the other two macronutrients—phosphorous and potassium—were not altered during the drying process.

Analysis of two grab samples of American Samoa soil used in subsequent plant-growth studies is shown in Table 4. This soil has a gravel content of 48% and is deficient in nitrogen, phosphorous, potassium, sulfur,

Table 4
Chemical Analysis of Soil Samples Obtained from American Samoa

Parameter	Grab sample #1	Grab sample #2
Moisture	10.9%	10.3%
pH	7.6	7.6
EC dS/m	0.1	0.1
Lime (estimate)	Low	Low
Org. matter	0.6%	0.3%
Gravel	48.2	48.5
Texture	Sand	Sand
Sand	94.0%	94.0%
Silt	4.0%	4.0%
Clay	2.0%	2.0%
NH_4 HCO_3-DTPA extract (mg/kg)		
NO_3-N	1	2
Phosphorous	5.7	3.1
Potassium	49.0	53.3
Iron	13.6	15.1
Manganese	0.5	0.4
Zinc	8.4	6.3
Copper	0.8	0.8
Totals		
Nitrogen	<0.001%	<0.001%
Phosphorous	0.079%	0.082%
Potassium	0.153%	0.143%

and manganese, which may severely restrict plant growth. Additionally, the high-sand, low organic content of this soil reduces its water- and nutrient-binding capacity.

Greenhouse plant-growth studies at Colorado State University were conducted in triplicate using a random-block design as shown in Fig. 1. Corn plants grown in unamended Samoan soil demonstrated deficiencies in nitrogen, phosphorous, sulfur, and potassium within 4 wk of planting. Corn plants grown in either anaerobic compost showed no such deficiencies in the same period. Significant differences in corn plant growth became evident with Samoan soil compost amendment at the 6-wk growth period (*see* Fig. 2). Following harvest of all replicates at 6 wk, plants from each pot were analyzed for plant dry matter and nutrient composition. The data shown in Fig. 3 indicate that increasing the level of anaerobic compost amendment (in t/ha) results in a proportional increase in corn plant dry matter. The data indicate that the MSW/nutrient-solution compost was slightly better in this respect than compost from the digestion of MSW/tuna sludge. Additionally, neither compost demonstrated nutrient saturation over the range of application rates studied.

Fig. 1. Organization of the random-block design used in the greenhouse plant-growth studies. Triplicate pots were used for each set of compost amendments to Samaon soil.

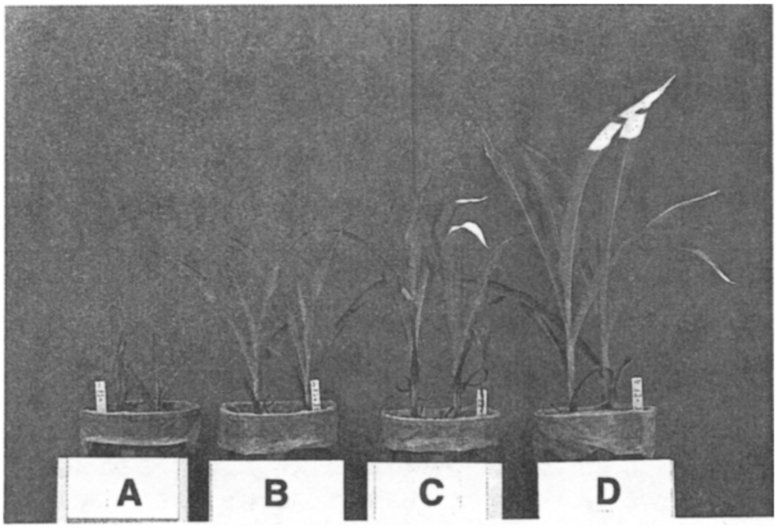

Fig. 2. Influence on the growth of corn with increasing levels of MSW/tuna-sludge compost addition to Samsoan soil. Crops were photographed at 6 wk of growth, just prior to harvest. Amendment levels were as follows: (A) none, (B) 15 t/ha, (C) 30 t/ha, and (D) 45 t/ha. Lighter color on leaves of taller plants was the result of light effects and not nutrient deficiencies.

Additional benefits of water-nutrient-binding capacity of soil through the amendment of Samoan soil with anaerobic compost was measured prior to plant-growth studies by determining the enhancement in field capacity with compost amendment levels. The data in Fig. 4 indicate proportional increases in the Samoan soil field capacity with increasing amendment levels of MSW/tuna-sludge compost.

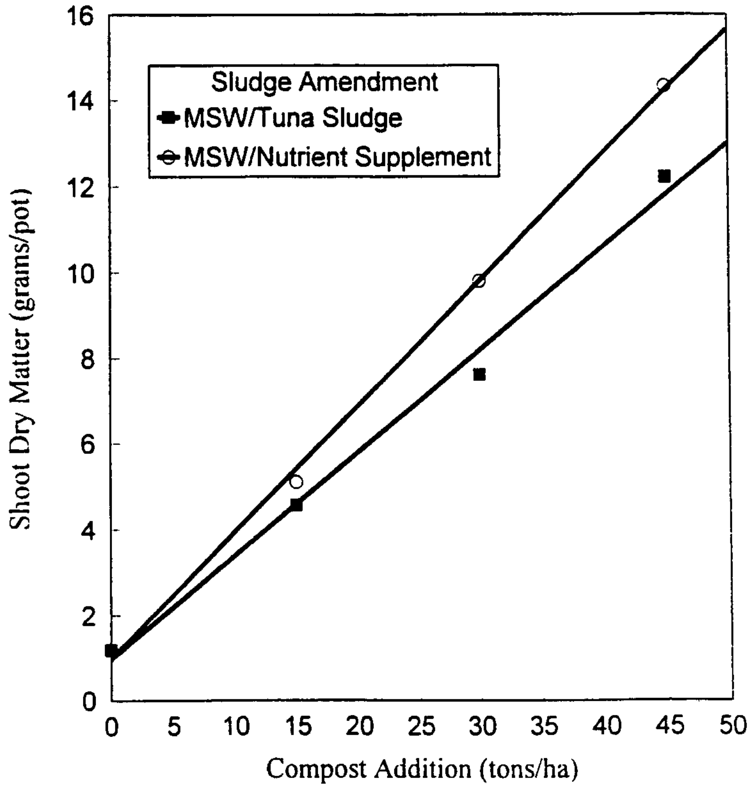

Fig. 3. Effects of anaerobic compost addition to Samoan soil on plant dry matter. Plants were harvested at 6 wk. Data points represent the average of triplicate samples.

DISCUSSION

The high-solids anaerobic consortium rapidly adapted to stable conversion of the MSW/tuna-sludge feedstock. High-solids anaerobic digestion of the combined MSW/tuna-sludge feedstock resulted in a stable fermentation with high feedstock COD conversion at an aggressive organic loading rate. The anaerobic conversion of the combined MSW/tuna-sludge feedstock also resulted in an elevated methane content of the biogas product, consistent with the conversion of a more-reduced feedstock. The addition of tuna sludge not only served to supply nutrients required for effective MSW bioconversion, but in fact enhanced the bioconversion of the MSW portion of the feedstock.

Air-drying of high-solids digestion process residues for compost production resulted in the loss of > 95% of the ammonia nitrogen, suggesting that standard dewatering equipment, such as screw or belt presses, would be more appropriate and would conserve the ammonia nitrogen content of the compost. When amended to native Samoan soil, both anaerobic compost materials resulted in proportional increases in corn dry matter production. Average plant dry matter production at the 45 t/ha amend-

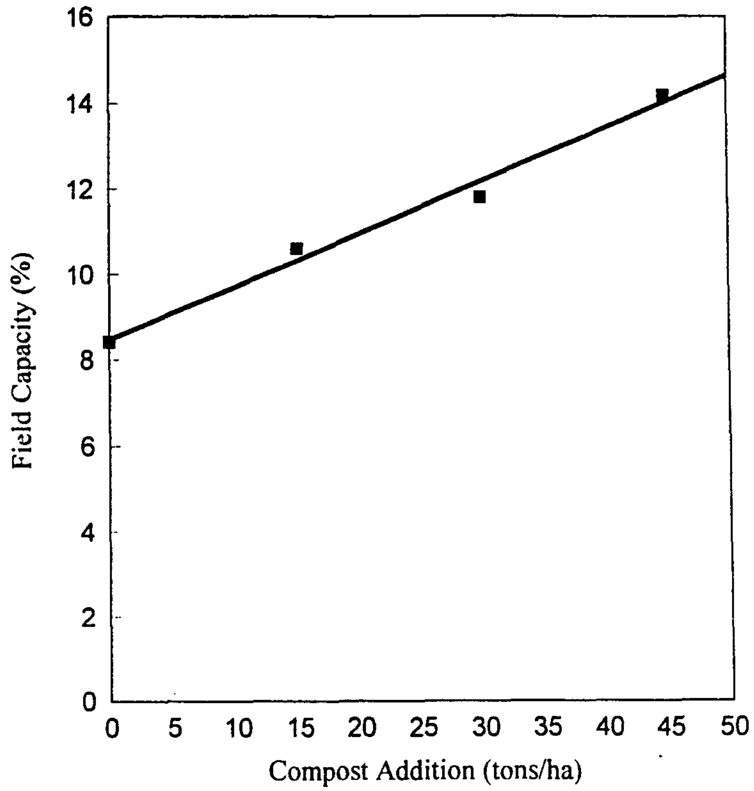

Fig. 4. Effects of anaerobic compost addition (from MSW/tuna-sludge digesters) to Samoan soil on field capacity. Increasing field capacity (water-holding capacity) also is indicative of enhanced cation-exchange capacity of the soil.

ment level represented 70–89% of that obtained under optimized conditions with chemical fertilizer addition. Within the confines of greenhouse pot studies, neither nutrient saturation nor plant-growth inhibition was determined over the range of compost amendment levels tested. This result indicates that further increases in the level of compost amendment byeond 45 t/ha may result in additional increases in crop production. For high-nutrient-demanding crops, such as corn, additional supplementation of the MSW/tuna sludge with superphosphate may be necessary for optimum use with the Samoan soil type.

A major problem with both aerobic and anaerobic composts is the presence of high salt levels, which if allowed to build up may be toxic in some plants. We therefore recommend that application rates and soil salt concentrations be monitored for such effects consistent with the general use of compost products.

Additional benefits of compost application to sandy soils, such as that from American Samoa, are the enhancement of water retention and nutrient-binding capacity by virtue of increased soil organic matter. Studies confirmed that increasing the level of anaerobic compost resulted in proportional increases in the field capacity of Samoan soil.

In summary, although the benefits of anaerobic bioconversion of organic wastes are well known with respect to fuel-gas production and use, little is known about the utility of anaerobic residues. This study indicates that the anaerobic compost produced from the anaerobic digestion of MSW and tuna sludge is compatible with Samoan soil and enhances the level of important plant-growth nutrients, as well as the soil's water retention and nutrient-binding capacity.

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REFERENCES

1. US Environmental Protection Agency (February 1989), *Final Environmental Impact Statement for the Designation of an Ocean Disposal Site off Tutuila Island, American Samoa for Fish Processing Wastes*, US EPA Region 9, San Francisco, CA.
2. *Honolulu Advertiser* (August 4, 1990) Sect. C, p. 1.
3. Metcalf & Eddy, Inc. (1979), *Wastewater Engineering: Treatment, Disposal, Reuse*, McGraw-Hill, New York.
4. US Environmental Protection Agency (1979), *Process Design Manual for Sludge Treatment and Disposal*, EPA 625/1-79-011, Environmental Research Information, Cincinnati, OH.
5. Arora, M. L. (1980), *Water and Sewage Works* **127**, 24.
6. Rivard, C. J. and Nagle, N. J. (1992), in *Proceedings of the 1992 Food Industry Conference*, Georgia Tech Res. Inst., p. 119.
7. Rivard, C. J., Vinzant, T. B., Adney, W. S., Grohmann, K., and Himmel, M. E. (1990), *Biomass* **23**, 201.
8. Rivard, C. J., Himmel, M. E., Vinzant, T. B., Adney, W. S., Wyman, C. E., and Grohmann, K. (1989), *Appl. Biochem. Biotechnol.* **20/21**, 461.
9. Henson, J. M., Bordeaux, F. M., Rivard, C. J., and Smith, P. H. (1986), *Appl. Environ. Microbiol.* **51**, 288.
10. Greenberg, A. E., Conners, J. J., and Jenkins, D., eds. (1981), in *Standard Methods for the Examination of Water and Wastewater, American Public Health Association*, Washington, DC.
11. Rivard, C. J., Himmel, M. E., and Grohmann, K. (1985), *Biotech. Bioeng. Symp.* **15**, 375.
12. Owen, W. F., Stuckey, D. C., Healy, J. B., Young, L. Y., and McCarty, P. L. (1979), *Water Res.* **13**, 485.
13. Workman, S. M., Soltanpour, P. N., and Follett, R. H. (1988), *Technical Bulletin LTB88-2*, Colorado State University, Fort Collins, CO.