FACTORS AFFECTING DISINFECTION AND STABILIZATION OF SEWAGE SLUDGE

Bethany AnnMadge Acquisto,* Robert S. Reimers,** James E. Smith, Jr.*
and Suresh D. Pillai**
*U.S. Environmental Protection Agency
Office of Research and Development
MS-G75
26 West Martin Luther King Dr.
Cincinnati, OH 45268

**Tulane University
***Texas A&M University

ABSTRACT

Effective disinfection and stabilization of sewage sludge prior to land application is essential to not only protect human health, but also to convince the public of its benefits and safety. A basic understanding of the key factors involved in producing a stable biosolid product is a necessary component to ensuring that effective disinfection and stabilization are achieved. Key stressors used to treat sewage sludge, both traditional and some emerging, are discussed including physical, chemical, and biological stressors. Factors that affect a stressor's effectiveness are included where information is available. Examples of methods that employ each stressor are presented.

KEYWORDS

sewage sludge, disinfection, stabilization, temperature, pH, irradiation, desiccation, pressure, ultrasound, caviation, oxidants, non-charged chemicals, biochemical by-products

INTRODUCTION

Sewage sludge resulting from municipal wastewater treatment must be treated in accord with federal and state requirements prior to being applied to land as a soil amendment, providing conditioning and fertilizing benefits. Such treated sludges are commonly referred to as biosolids. The most current data indicates that land application of biosolids is the most common use/disposal option for sewage sludge at 60% (NRC, 2002). Several factors are expected to continue pushing the use of biosolids on land upwards. These factors include a decreasing pool of use/disposal options to choose from, increasing costs of landfilling, and increasing air controls on incineration. Estimates are that only 0.1% of available agricultural land in the United States has biosolids land applied annually (NRC, 2002). Thus, a tremendous untapped market exists to support such expansion in the use of biosolids.

Despite the expected growth in the land application of biosolids, public acceptance of the practice has lagged behind. Because of these external pressures care must be taken to produce the best possible product. This entails a basic understanding of the key factors involved in producing a stable biosolids product.

Although there has been some debate over the exact definition of stabilization, it generally includes three main parts:

1. pathogen reduction or disinfection,
2. elimination of offensive odors and a general improvement of aesthetics,
3. minimization in the potential for putrification.

The 40 CFR 503, Standards for the Use or Disposal of Sewage Sludge breaking sludge stabilization into two main sets of regulations laid out in Subpart D, Pathogens and Vector Attraction Reduction. This subpart provides alternatives for achieving pathogen reduction in sewage sludge. The pathogen reduction requirements are divided into two levels, Class A and Class B, depending upon how complete the disinfection. In Class B, disinfection is incomplete; indicator organisms (namely, fecal coliform) are reduced by approximately two logs to densities below 1 million per gram of total solids (g TS) dry weight and pathogens are reduced by approximately 10%. Processes which produce a Class B product are called PSRPs or processes which significantly reduce pathogens. In Class A, disinfection is more complete; fecal coliform levels are less than 1,000 MPN/g TS-dry weight and pathogens are reduced below the level of detection. Processes which produce a Class A product are called PFRPs or processes which further reduce pathogens. Many of these disinfection alternatives, regardless of class will simultaneously reduce the attractiveness of a sludge to vectors, such as digestion and alkaline treatment, but some alternatives may require partnering with a separate vector attraction reduction option.

Vectors are attracted to sewage sludge because it is a possible food source. Typically, they are tipped off to a food source by offensive odors produced by any remaining putrescible materials. Vector attraction reduction is accomplished in two main ways, oxidative treatment or physical barriers in which the sewage is injected under or incorporated into the topsoil. Treatment can be accomplished biologically in which the available food source is consumed or oxidized by microorganisms or chemically/physically in which the environment within the sewage sludge is changed such that microbial activity cannot be supported. Technically speaking, a stable sludge will undergo no further change. Thus, permanent stabilization can only be achieved by a biological vector attraction reduction option. Vector attraction reduction through chemical or physical treatment options, such as lime stabilization and desiccation are temporary, because these options do not remove the underlying cause of putrification and odors, i.e., the food source.

The remainder of this paper will review the key factors or stressors involved in traditional and some emerging disinfection/stabilization methods in contemporary literature. More detailed descriptions of all the traditional methods called out in part 503D can be found in U.S. EPA (2003).

KEY FACTORS INVOLVED IN PRODUCING A STABLE BIOSLIDS PRODUCT

All traditional and emerging disinfection methods reviewed herein are listed in Table 1. Although many methods incorporate more than one type of stressor, the disinfection technologies can be broken down into three main groups based upon their primary stressor or factor.

Table 1: Key Factors in Disinfection/ Stabilization Methods for Sewage Sludge

Disinfection/Stabilization Method	Temp	pH	Irradiation	Desiccation	Pressure	Ultrasound/ Cavitation	Oxidant Chemicals	Non-charged Chemicals/ Biochemical by-products
Physical Methods								
Thermal Treatment	●							
Heat Treatment[1]	●				●			
Pasteurization[1]	●							
Heat Drying	●			●				
Air Drying	●		●	●				●
Gamma Rays[1]			●					
Electron Beam (Beta Rays)[1]			●					
Microwaves[1]			●					
Homogenization[2]					●	●		
Ultrasonics[2]	●				●	●		
Biological Methods								
Aerobic Digestion	●							●
Anaerobic Digestion	●							●
Composting	●			●				●
Chemical Methods								
Alkaline Treatment	●	●		●				●
Lime Stabilization		●						●
Ferrate (VI) Oxidation		●					●	
Ozone (Synox)[1]		●			●		●	
Chlorine Dioxide (Neutralizer)[1]		●					●	●
Hydrogen Peroxide[1]							●	
Acid-Liming (Bioset)1	●	●		●	●			●

[1]Achieves disinfection but typically requires additional processing for solids stabilization
[2]Typically used as pretreatment to a biological method

Physical Stressors
Physical stressors include temperature, desiccation, irradiation, pressure, and ultrasound and cavitation. These stressors can solubilize organics, destroy cell membranes, and breakdown DNA or other critical cellular structures.

Time and Temperature
Excessive temperature is the most common stressor in sewage sludge disinfection. Of the 20 disinfection methods listed in Table 1, 50% of them utilize elevated temperatures to some degree. The effects of time and temperature on selected pathogens and indicator organisms are generally well established. A useful graph of time-temperature curves was developed in Europe and can be found in Strauch (1998). What they call the "safety zone" or the area on the graph where the time-temperature combinations are above that which the selected pathogens can survive is bordered by enteric viruses on the high temperature/short time period end and *Ascaris* ova on the lower temperature/longer time period end. Key points along their safety zone include: > 62°C at one hour, > 50°C for one day, and > 46°C for one week (Strauch, 1998). These time-temperature combinations are much less conservative than was suggested by Mbela (1989) in his research regarding the effect of temperature on the inactivation of *Ascaris* ova in aerobic and anaerobic digestion systems. At a lower temperature (45°C) where Ascaris is thought to be the most thermally resistant pathogen, 30 to 50 days under anaerobic and aerobic conditions respectively, was required for complete disinfection.

Three primarily thermal processes are listed under part 503D, Class A, Alternative 1, thermal treatment, and two PFRPs, heat treatment and pasteurization. Thermal treatment regulations lay out a set of four time-temperature equations. The way by which the temperature is increased is not dictated. Thus, countless processes may be covered by this alternative. Microwave processing is one example which will be discussed later. Heat treatment is a process used for liquid sludges only. It typically involves steam injection in a pressurized vessel. Temperatures of 180°C or higher must be maintained for 30 minutes. Pasteurization is similar to heat treatment, but it is not limited to liquid sludges and the minimum temperature is much lower (70°C). The contact time remains at 30 minutes or longer. Pasteurization conditions can be achieved through use of heat exchangers, steam injection and even quicklime addition which take advantage of the rapid exothermic reactions created. Properly designed use of quicklime for pasteurization has the added advantage of meeting vector attraction reduction requirements through option 6 (pH adjustment). Other methods of pasteurization and heat treatment typically require additional treatment to reduce vector attraction. Since time and temperature disinfection methods do not remove the food source, they are only temporarily stable and care must be taken not to contaminate or let the adverse conditions in the end product dissipate before use.

Desiccation
Two disinfection methods rely primarily on desiccation as a main stressor: heat drying and air drying. Heat drying is a PFRP that uses elevated temperature in combination with desiccation. The regulatory description of heat drying is a process that uses direct or indirect contact with hot gases (≥ 80°C) to reduce the moisture content of sludge to 10% or less. Several processes have been developed to achieve these conditions including flash dryers, spray dryers, steam dryers, and currently the most common, rotary dryers. After treatment the finished product must be

maintained at 90% solids content to comply with vector attraction reduction regulations. As long as this is followed the biosolids will remain in a state of temporary stability, but as in the time-temperature disinfection methods, heat drying does not remove the food source and thus rewetting and recontamination will cause unstable conditions to return.

Air drying is a PSRP. The process is relatively uncontrolled, relying on ambient environmental conditions to dry the sewage sludge over a minimum of three months, during which at least two of the months are required to have ambient air temperatures above freezing (i.e., > 0°C or 32°F). Typically, wet sludge is allowed to dry in shallow beds which are exposed to the atmosphere. This allows the sun's ultraviolet radiation to assist in disinfection, along with elevated temperatures (depending on local climate) and desiccation if a dry spell is experienced. The long holding period will also allow some biological degradation even if conditions are not always optimal for this stressor. This reduction in food source will lead to a greater permanency in the level of stability achieved, but typically air drying does not result in a fully stable biosolids product.

Irradiation

Radiation is listed in part 503D as a PFRP for sewage sludge disinfection. Radiation alters the colloidal nature of a cell's protoplasm causing cell death. Two types of radiation are listed in the regulation; (1) gamma (γ) rays which are emitted by a radioactive source such as cobalt-60 or cesium-137, and (2) beta (β) rays produced with an accelerator. Both require a dose ≥ 1.0 megarad. Gamma radiation systems, although economical, are not popular in the United States due to a lack of public acceptance of radioactive technologies. However, research in India using a cobalt-60 based gamma irradiator was recently published (Gautam *et al.*, 2005). The effect of different process parameters was studied in an effort to eliminate regrowth of coliform bacteria following treatment. It was determined that changing the system design from an entirely closed-loop system to an open-loop system allowed them to capitalize on oxygen's radio-sensitizing properties. The change preserved the systems 6-7 log reduction in total coliform following doses of 300-400 kRad while at the same time eliminating regrowth. Gautam *et al.* (2005) also reported enhancement of sludge dewatering properties and larger more productive growth of peanut plants growth in irradiated sludge as compared to non-irradiated sludge. These finding are additional advantages to using gamma radiation for the production of biosolids. Gamma radiation will provide some degradation and oxidization of organic pollutants (Gautam *et al.*, 2005) which will provide for some permanent improvement in stability, but typically irradiated sewage will require additional treatment to demonstrate vector attraction reduction.

Interest in ionizing beta radiation has resurfaced recently. Although true beta rays are produced following spontaneous decay of certain radioactive materials, such as tritium (an isotope of hydrogen), carbon-14, phosphorus-32, and strontium-90, part 503D specifically dictates that the beta radiation be from an accelerator. This type of radiation is more commonly known as electron beam radiation and is widely used in the food industry (Smith and Pillai, 2004). Electron beam is identical to a high energy beta ray, the difference is electron beams are produced from a non-radioactive source, so they don't have the public acceptance problems associated with gamma radiation. Capizzi-banas and Schwartzbrod (2001) performed laboratory tests using an electron beam accelerator on *Ascaris* ova. Their data indicated that ova were effectively inactivated to below the level of detection at doses between 100 and 120 kRad. A

Romanian research team, Martin *et al.* (2005), studied the use of electron beam to disinfect several bacteria, including *E. coli*, in waste sludge from a vegetable oil plant. They observed a 5 log reduction in *E. coli* with a 160 kRad dose. Thus, it appears that both bacterial indicators and helminth ova can be sufficiently disinfected at doses well below the required minimum of 1.0 megarad. Viruses, however, are reportedly substaintially more resistant to electron beam irradiation. Still, recent research suggests that viruses can be adequately disinfected at relatively low doses and even prions can be effectively inactivated at 4.4 megarads (Nickelsen *et al.*, 2005). Electron beam treated wastes will require a separate vector attraction reduction technique to achieve a stable product.

Microwave irradiation of sewage sludge is a relatively new application of this widely used technology. Microwaves, when passed through sewage sludge, cause water molecules in the sludge to vibrate constantly attempting to align themselves with the microwave frequency. This vibration produces frictional heat and the water will begin to boil just as in a home microwave oven. Water molecules inside pathogens and other sewage microorganisms will also try to escape causing the cells to "expand and then explode" (Alderman, 2004). Early research into microwave irradiation determined that microwave frequency can play a role in the efficiency of microwave systems. The lower microwave region, frequencies of 2450 MHz and less are capable of denaturing DNA molecules and disassociating organic chemical bonds (Reimers *et al.*, 2000). Use of these lower frequencies will allow for a more targeted application leading to a more cost effective treatment. Microwave disinfection was reported by Martin *et al.* (2005) who found 45 kW-s (90 s at 500 W) of microwave irradiation produced approximately a 4.8 log inactivation of *E. coli*. *Staphylococcus intermedius*, *Pseudomonas aeruginosa*, and viable *Trichinella spiralis* larvae were also significantly reduced with similar doses (16.5 – 22.5 kW-s) (Martin *et al.*, 2005).

More recent investigations using microwaves found complete inactivation of fecal coliform (i.e., to below detection limits) could be achieved with 60kW-s and 90kW-s (1kW for 60 and 90s) for primary and waste activated sludge, respectively (Hong *et al.*, 2006; Pino-Jelcic *et al.*, 2006). These doses resulted in corresponding temperature increases up to 65 and 85°C. The greater dose necessary for the waste activated sludge was reported to be the result of higher % total solids as compared to the primary sludge. Microwave energy is absorbed to varying degrees depending on the media's moisture content, ionic strength, percentage of protein and fat, and viscosity (Hong *et al.*, 2006). The thicker waste activated sludge was demonstrated to have a reduced penetration depth as compared to primary sludge (Hong *et al.*, 2006). Thus, solids content of sewage sludge appears to be a significant factor in the efficiency of microwave disinfection. When comparing their microwave disinfection results to those achieved with a conventional heating method (waterbath immersion), microwaves were more efficient for the primary sludge and equally as efficient for the waste activated sludge (comparisons were made on the basis of equal temperatures), but the microwave treatment achieved it's disinfection on the order of seconds compared to minutes for conventional heating (Hong *et al.*, 2006). Solubilization of organics was also found to be significantly greater using microwaves as compared to conventional heating (Pino-Jelcic *et al.*, 2006). Solubilization will increase the availability of easily digested food, thus microwave disinfection must be paired with additional treatment to avoid regrowth and recontamination problems.

To assist in stabilizing the sludge solids, microwaves also paired up with mesophilic anaerobic digestion (35°C). Class A limits for fecal coliform (1,000 cfu/gTS) were consistently met with a hydraulic retention time of 50 days following 60kW-s treatment of microwave irradiation (Hong *et al.*, 2006). Mesophilic anaerobic digester controls without any pretreatment and with conventional heating pretreatment could not achieve Class A limits consistently. Similarly, *Salmonella* spp. disinfection was significantly more effective with 85% of the microwave pretreated sludge samples reduced to the detection limit (2,000 cfu/L) (Pino-Jelcic *et al.*, 2006). Pino-Jelcic *et al.* (2006) also reported that microwave pretreatment improved biogas production and dewaterability, and significantly improved % volatile solids reduction as compared to the two controls. This is likely due to the increase in solubilization of organics produced using microwave pretreatment. Thus, using microwave irradiation as a pretreatment to mesophilic anaerobic digestion produces a more stable biosolids product in less time than digestion alone.

Still, microwave irradiation does not necessarily need to be designated as solely a pretreatment option. Independent full-scale microwave systems for the treatment of sewage sludge are already commercially available through Burch BioWave, Inc. (Alderman, 2004). Their first permanent operation was installed in Fredericktown, Ohio and began operating as a Class A process under Alternative 3 which requires microbiological monitoring of both the treated and the untreated sludge. Dewatered sludge (> 7% total solids) moves through their system in a thin layer on a conveyor belt. Microwave generators (75-100 kW) heat sludge to greater than 80°C for 6-14 minutes (Alderman, 2004). At this operating temperature/time combination the Burch BioWave microwave process is operating in accordance with Class A, Alternative 1 (Thermal Treatment). Thus, after consultation with the U.S. EPA's Pathogen Equivalency Committee, Burch BioWave, Inc. received a letter supporting a change in their permit from Alternative 3 to Alternative 1 in early 2005. This change will make the Burch BioWave process more economical by eliminating the need for extensive monitoring. Heated air and an exhaust blower assist in drying the sludge to 75 – 90% solids. Temperature and desiccation reduce the pathogens and provide at least temporarily stable conditions.

Finally, the combination of two types of irradiation, electron beams and microwaves, either in succession or simultaneously has proven to be particularly effective (Martin *et al.*, 2005). For all organisms tested (*E. coli*. *Staphylococcus intermedius*, *Pseudomonas aeruginosa*, and viable *Trichinella spiralis* larvae) the combination of electron beams and microwave irradiation produced a greater lethal effect than either of the irradiation types alone. At lower doses the combined irradiation appeared to have a synergistic effect; however, this effect was not observed at the higher doses studied (Martin *et al.*, 2005).

Pressure and Ultrasound/Cavitation

The final physical stressors are pressure and ultrasound or hydraulically-produced cavitation. Although several sludge disinfection technologies use increases in pressure to enhance the action of other stressors, no technology uses excessive pressure as the primary stressor. However, rapid changes in pressure play a significant role in cavitation produced hydraulically or by ultrasound. Cavitation processes have been shown to inactivate more resistant microorganisms such as protozoan oocycts and *Ascaris* eggs (Reimers *et al.*, 2005), but commercially available units are only just emerging onto the market. A high-pressure homogenization technology has recently been developed by a German environmental research and development institute (Adell, 2005).

The homogenizer is a flow-through valve which rapidly increases the velocity over 50-fold causing cavitation, sharp changes in pressure, turbulence, and other liquid stresses. Although no actual microbiological data was provided, the manufacturer claims that the homogenizer provides "effective mechanical disruption of sludge microorganisms" (Adell, 2005). In small scale field studies using the homogenizer as a sludge pretreatment to anaerobic digestion, the system resulted in 30% higher biogas production and 23% sludge reduction over anaerobic digestion alone. These benefits were likely due to solubilization of organics caused by the extreme conditions of hydraulically produced cavitation (Adell, 2005).

Ultrasound produced cavitation for the pretreatment of sewage sludge has also been investigated in Germany (Tiehm *et al.*, 1997). Ultrasound has been shown to produce significant disinfection in wastewater due to extreme temperatures, pressures, and mechanical stresses associated with cavitation (Madge and Jensen, 2002). As with the homogenizer, the effect of ultrasound on sewage sludge microorganisms was not studied by Tiehm *et al.* (1997), however, following a 230 kW-s ultrasound pretreatment, anaerobic digesters reached what the authors considered stable conditions (44.3% volatile solids reduction) within only 8 days at 37°C. A control digester operated without the ultrasound pretreatment required a 22 day residence time to reach a similar level of stability (45.8% volatile solids reduction) (Tiehm *et al.*, 1997). Thus, the ultrasound cut the required treatment time by 64%. Additionally, biogas production rates were enhanced and overall sludge volumes were reduced. Although these examples of cavitation processes did result in solubilization of organics, additional treatment was required to produce a stable product. The pairing with anaerobic digestion has proved to significantly increase the efficiency of digestion and ultimately produce a permanently stable product.

Biological Stressors

The biological stressors are biochemical byproducts of biological activity. Such chemicals fall into the category of non-charged disinfectants. They include ammonia, amines, organic acids, aldehydes, and ketones (Reimers *et al.*, 2005). Metabolites like ammonia, volatile fatty acids, and hydrogen-sulfide are known to have toxic effects on microorganisms (Iranpour *et al.*, 2006). Volatile fatty acids can be a potent bactericide when in their protonated form which occurs at low pHs (Aitken *et al.*, 2005). Free ammonia is a metabolite of protein degradation (Park *et al.*, 2006). Elevated concentrations of free ammonia have been shown to contribute to the inactivation of viruses and *Ascaris* ova (Aitken *et al.*, 2005). The three biological sludge treatment methods, aerobic digestion, anaerobic digestion, and composting, make use of these non-charged disinfectants by encouraging microbial degradation through increased temperatures and control of the dissolved oxygen concentrations. Increases in temperature can be either external or autothermal energy produced by the biological activity itself. Once the available organics have been consumed, the lack of an available food source will then limit further microbial activity. Composting processes, especially windrow and static aerated pile methods, also use desiccation as a stressor. As discussed in the introduction, biological methods will produce the highest level of permanent stability since pathogen reduction is accompanied by a degradation of the food source, thereby limiting the chance for future putrification and odor production. Even in the case of recontamination, the lack of available food will keep regrowth to a minimum as large microbial populations simply cannot be support.

All three biological methods listed in Table 1 can be operated as a PSRP or a PFRP. The conditions of each process as listed in part 503D and what is commonly known at the White House document (U.S. EPA, 2003) are given in Table 2.

Table 2: Biological sludge Stabilization Methods

PFRP/ PSRP	Method	Time & Temp	Additional Requirements
PSRP	Mesophilic Aerobic Digestion	40 days @ 20°C up to 60 days @ 15°C	Agitated with air or pure oxygen to maintain aerobic conditions
	Mesophilic Anaerobic Digestion	15 days @ 35-55°C up to 60 days @ 20°C	Closed to the atmosphere to maintain anaerobic conditions
	Composting (Windrow, Static Aerated Pile, or Within-Vessel)	40°C for 5 consecutive days	None
PFRP	Thermophilic Aerobic Digestion	55-60°C for 10 consecutive days	Agitated with air or pure oxygen to maintain aerobic conditions
	Autothermal Thermophilic Aerobic Digestion*	56-57°C for at least 16 hours during a total treatment time of 6 days	Two reactors in series; Agitated with air to maintain aerobic conditions
	Two-Phase Thermo-Meso Feed Sequencing Anaerobic Digestion (2PAD)*	Phase 1: 49-55°C for 2.1 days Phase 2: 37°C for 10.5 days	Phase 1: 55°C must be maintained for at least 3 hours during the 2.1 days
	Composting (Within-Vessel or Static Aerated Pile)	55°C for 3 consecutive days	None
	Composting (Windrow)	55°C for 15 consecutive days	Minimum of 5 turnings

* Equivalent to a PFRP

Several other varieties of these processes exist. Three notable examples include the Columbus Biosolids Flow-Through Thermophilic Treatment ($CBFT^3$) process, the Los Angeles Continuous/Batch Thermophilic Anaerobic Digestion (LA-CBTAD) process, and Vermitech's Vermicomposting process. $CBFT^3$ has recently received a conditional site-specific PFRP equivalency from the U.S. EPA's Pathogen Equivalency Committee for their process design which is currently being constructed at the South Columbus, Georgia Water Resource Facility. The $CBFT^3$ process is a four stage, entirely anaerobic process. It consists of a pre-heat tank, a continuously fed, mixed digester (≥ 53ºC, ≥6.0 d), a plug-flow reactor (≥60ºC, ≥30m), and a mesophilic digester. Recommendation of equivalency for this process is significant because it is the first process to use a continuously fed, mixed digester.

The Los Angeles Hyperion Plant's LA-CBTAD process is already in place and has been operating under Class A, Alternative 3 since November 2002. LA-CBTAD is a two-stage process consisting of a continuous mode anaerobic digestion with a hydraulic retention time of ~11 days @ 53.4ºC followed by a second stage of anaerobic digestion operated in cycles of feeding, holding, and withdrawal with a guaranteed holding time of > 15 hours @ 53.6ºC. Routine monitoring for regulatory compliance has proven the LA-CBTAD process to be quite effective at pathogen reduction.

Vermitech has an operating demonstration of its vermicomposting process in Granville, PA which has been operating as a Class A facility since late 2004 under alternative 4 (testing of an unknown process). The proprietor claims that adding worms to the composting material allows vermicomposting processes to lower the temperature or time requirements below that of traditional composting. Some preliminary data to support this claim was collected. The actual method of disinfection provided by worms is unknown, but it has been suggested that the physical grinding conditions from moving through the worm's gut and contact with secretions produced by the worm which may have bactericidal and/or virucidal properties may be the underlying cause.

Recently several investigations have been made into characteristics of upstream plant operations that affect the stabilization efficiency of biological sludge treatment processes. Bolzonella *et al.* (2005) conducted a study into the effect of sludge age (i.e., sludge retention time or mean cell residence time of the wastewater activated sludge tanks) on mesophilic anaerobic digestion. They found that, in general, an increase in sludge age lead to decreases in gas production and % volatile solids reduction when the data was normalized to digester retention time. Thus, operation of the activated sludge tanks at a lower mean cell residence time should improve anaerobic digester performance and increase product stability. Wastewater treatment using membrane bioreactors appears to significantly affect the digestibility of sludge. Percent volatile solids reduction was significantly lower (approximately 35%) in membrane bioreactor sludge as compared to a conventional waste activated sludge following 30 days of batch digestion under both aerobic and anaerobic conditions (Holbrook *et al.*, 2005). Under anaerobic conditions the vector attraction reduction requirement of 38% volatile solids reduction could not be consistently met with the membrane bioreactor sludge (average = 34%) (Holbrook *et al.*, 2005). It was met under aerobic conditions (average = 43%) however, suggesting that aerobic digestion may be the preferred digester option for the treatment of membrane bioreactor sludges.

Park *et al.* (2006) performed an in-depth evaluation of the digestibility of waste activated sludges under aerobic and anaerobic conditions. They determined the factors they measured that affect anaerobic digestion are the use of iron flocculation in upstream processes and the presence of sodium. Iron used in flocculation binds to proteins and prevents them from being lost with the water stream, instead carrying them to the digesters. Once under anaerobic conditions the iron will be reduced, releasing the proteins, which are then available for microbial degradation. Sodium however appears to counteract the process in some way. Using waste activated sludge samples from nine full-scale treatment processes, the resulting % volatile solids reduction from a 30 day batch anaerobic digestion at 25°C could be predicted with a high level of confidence (R^2 =0.96) by the ratio of iron to sodium concentration in the untreated sludge (Park *et al.*, 2006). Aerobic digestion was not affected by iron or sodium. Thus, facilities with high iron concentrations and low sodium concentrations will be more likely to produce a superior biosolid using anaerobic digestion. Aerobic digestion was associated strongly with the concentration of divalent cations (Park *et al.*, 2006). High concentrations of magnesium and calcium lead to an increase in % volatile solids reduction, indicating that for plants with these conditions aerobic digestion may be a better option. As a final piece of their research Park *et al.* (2006) showed that combining aerobic and anaerobic digestion in a two-stage process, regardless of which is first results in the most stable sludge, as it appears that some organics can only be degraded in the presence or absence of oxygen. Such combined processes are just recently showing up on the market as efficient solids reduction processes, such as the U.S. Filter Cannibal Process (Sheridan and Curtis, 2004).

Chemical Stressors

The chemical stressors include pH, oxidants, and non-charged disinfectants which are not produced by biological activity, but either added directly or produced through chemical reactions. Some chemicals may also produce exothermic reactions bringing increased temperatures into play.

pH

Several processes employ changes in pH as their main stressor. Increases in pH are the most popular. Alkaline treatment, lime stabilization, and ferrate (VI) oxidation all fall into this category. Alkaline treatment is a PFRP. The process entails elevating the pH to 12 and maintaining it at 12 or above for over 72 hours during which the temperature must also increase to above 52°C for at least 12 hours. Following the period of elevated pH, the sludge must be dried to over 50% solids. Lime stabilization is a PSRP. Its requirements are less stringent requiring only that the pH be elevated to 12 and maintained for 2 hours. Unlike alkaline stabilization which does not specify what material must be used to raise the pH, some form of lime including hydrated lime, $Ca(OH)_2$; quicklime, CaO; or lime containing cement kiln dust, portland cement, or fly ash must be used to satisfy the requirements for lime stabilization (U.S. EPA, 2003). However, there is a benefit to using quicklime for alkaline treatment because it creates exothermic reactions which are capable of raising the temperature above 50°C which may eliminate or at least alleviate the energy requirements necessary to meet the time-temperature requirement. Both alkaline treatment and lime treatment also produce high ammonia concentrations through chemical reactions that assist in disinfection. The higher temperatures in alkaline treatment increase the effectiveness of ammonia as a disinfectant such that it plays a primary role in the actual disinfection accomplished using this method (Reimers *et al.*, 2005). Some research using ammonia hydroxide (NH_4OH) as the agent for alkaline treatment seems to support this statement. Ghiglietti *et al.* (1997) found that the inactivation of *Ascaris* ova was more closely associated with the ammonia concentration than with the resulting pH. They performed their experiments at room temperature (22°C) and still achieved inactivation of *Ascaris* ova as long as ammonia hydroxide concentrations were 1% or above.

Ferrate (VI) (FeO_4^{2-}) when added to sewage sludge reacts with water and creates not only high pH conditions, but also acts as a powerful oxidizing agent as shown by the following reaction (de Luca *et al.*, 1996):

$$2\ FeO_4^{2-} + 3\ H_2O \rightarrow 2\ FeO(OH) + 1.5\ O_2 + 4\ OH^-$$

Ferrate (VI) has been proposed for use as the agent responsible for alkaline treatment or as an alternative or equivalent to lime stabilization. Inactivation of bacteria (e.g., *Clostridium perfringens*), viruses, and helminth ova using ferrate as a disinfectant have been reported (Reimers *et al.*, 2005). The benefit of using ferrate (VI) over lime is that its oxidizing powers significantly reduce nuisance odors typical of liming by transforming sulphides into sulphates and ammonia into nitrate (de Luca *et al.*, 1996).

These elevated pH treatment methods create temporary stabilization. Pathogens are reduced and the hostile environment created prevents re-contamination or regrowth from causing putrefying and odiferous conditions. However, the food source remains relatively untouched. Thus, care must be taken to either maintain the hostile conditions until time of use, or prevent re-contamination.

Acid trimming agents or acidic pH conditions can also be used as a disinfecting stressor. Chemicals such as sulfuric acid, nitric acid, phosphoric acid, and sulfamic acid, and sodium bisulfate can all be used for this purpose. Examples include sulfuric acid used in the Synox and Neutralizer processes, and sulfamic acid used in the Bioset process, all three of which are dominated by other stressors and will be discussed elsewhere. Acid trimming agents or acidic pH conditions are typically only used as secondary stressors.

Oxidants

Oxidants with disinfecting power which have at some point been suggested for the treatment of sewage sludge include ozone, peroxide, ferrate, chlorine dioxide, chlorite, chlorate, hypochlorite, and hypochlorous acid. Recently, ozone, chlorine dioxide, hydrogen peroxide, and ferrate (as discussed above) have been actively pursued in the literature and elsewhere.

Ozone has an established process, Synox OxyOzonation, which has received equivalency from the U.S. EPA's Pathogen Equivalency Committee to operate as a PSRP and a PFRP. The process involves acidifying sludge with sulfuric acid, treating it with ozone for 1 hour under pressurized conditions, then depressurizing and treating with nitrous acid for 2 hours (U.S. EPA, 2003). Specific conditions such as pH, ozone dose, and nitrite (converts to nitrous acid) dose are more stringent with the PFRP as compared to the PSRP. Ozone has also been in the literature lately as a part of the wastewater recycle treatment train (Ahn *et al.*, 2002). The ozone was operated in semi-batch mode and waste sludge was thickened directly in, then drawn off from, the ozonation tank. Operating in this fashion, it was found that the amount of sludge was reduced by up to 40% depending on the ozone dose (Ahn *et al.*, 2002). Dewaterability also improved following ozonation. Although the ozone dose was optimized for solids solubilization in this study, it may be possible to use this same concept and optimize for pathogen reduction and stabilization as well.

Chlorine in all its various forms is widely used in wastewater disinfection on the water stream, but not often used on the residuals waste stream. The high solids content in the sludge stream interferes with the disinfecting action of chlorine making it much less effective. However, there are some instances where chlorine is used as a primary disinfectant of sewage sludge. For instance, chlorine dioxide is employed as the primary stressor in the Neutralizer Process, an emerging process that is currently in the equivalency review process. The Neutralizer Process is an acid-oxidative process similar to Synox but substituting chlorine dioxide for ozone. The substitution of chlorine dioxide reportedly makes this process more efficient than the Synox process because the external pressure conditions of 60 psi necessary to keep to ozone in contact with the sludge are unnecessary when using chlorine dioxide (Pratt *et al.*, 2005). The Neutralizer process is a batch operation with four main steps: (1) chlorine dioxide is added to a closed system and continuously mixed for 2 hours; (2) sulfuric acid is added to reduce pH to approximately 2.5; (3) nitrite is added to form nitrous acid and continuously mixed for an additional 2 hours; and (4) lime is added to equalize pH before dewatering. The triple stress of chlorine dioxide, low pH, and nitrous acid all work together to disinfect pathogenic organisms.

Extensive laboratory testing has been carried out at Tulane University to support this statement using helminth eggs, bacteria, bacterial spores, and viruses (Pratt *et al.*, 2005).

Hydrogen peroxide (H_2O_2) is a powerful oxidizing agent. Bench scale tests are underway to support PFRP equivalency of ElectroIonic Processing by Bioelectromagnetics, Inc. In this process a high frequency electrolytic field is used to produce hydrogen peroxide in an electro-ionic reaction. The hydrogen peroxide is then used as the primary stressor for disinfection. Tests to support this technology are being performed in Jackson, MS on mesophilically digested sludge. In addition to disinfection, hydrogen peroxide also converts organic compounds to carbon dioxide and water, and inorganic compounds to less toxic forms. Thus, hydrogen peroxide treatment will provide some level of permanent stabilization. The other oxidizers discussed above should also provide a similar level of permanent stability; however, it is doubtful that the stability achieved by oxidation alone is enough to pass vector attraction reduction regulations, such as percent volatile solids reduction or specific oxygen uptake rate.

Non-Charged Chemicals

Non-charged chemicals, excluding those which are biologically produced (see the Biological Stressors section for a discussion on these non-charged disinfectants) include nitrous acid, peracetic acid, and chemically produced ammonia and amines. Non-charged chemicals do not produce any solids stabilizing effects. Thus, they must be paired with other treatment methods to achieve a usable biosolids product.

Ammonia and amines are chemically produced in alkaline treatment and lime stabilization where they play a secondary (or possibly co-primary) disinfectant role to pH conditions as discussed above. Chemically produced ammonia is thought to be the primary stressor in the Bioset process. The Bioset process is a relatively new, acid-liming treatment process. It is a multi-stressor process developed for use with sewage sludge utilizing elevated temperatures, pH extremes, desiccation, pressure, oxidant chemicals, and non-charged chemicals (see Table 1). The process begins by mixing lime and sulfamic acid into dewatered sludge. The mixture then moves through a plug-flow reactor designed to hold a temperature of 55°C. Internal pressures of 30 psi develop within the reactor during its 25 minute residence time. Ammonia produced by the lime addition can reach concentrations in the reactor above 1% (10,000 mg/L) on a volume basis under the conditions of the Bioset process. Extensive pilot scale testing of the Bioset process has been conducted by Tulane University to support a PFRP national equivalency. Thus far a site-specific equivalency has been recommended at Kingwood, TX. Five additional pilot installations are under review and a national equivalency is pending.

Nitrous acid is used as a secondary stressor in the Synox and Neutralizer processes as described above. However, its importance to the overall effectiveness of these processes in producing a Class A material is clear. During development of the Synox and Neutralizer processes it was found that regardless of the oxidant used (ozone or chlorine dioxide) *Ascaris* ova were relatively resistant to oxidant chemicals (Pratt *et al.*, 2005). Thus inclusion of nitrous acid into the process at low pH was necessary to inactivate helminths, while the oxidant was thought to be primarily responsible for inactivation of the remaining organisms.

Finally, peracetic acid has been demonstrated in laboratory studies to be an effective disinfectant in sewage sludge (Barrios *et al.*, 2004). Peracetic acid was formed by adding hydrogen peroxide and acetic acid together. Fecal coliform, *Salmonella* sp. and helminth ova were all significantly reduced at peracetic acid concentrations of 550 ppm (Barrios *et al.*, 2004).

SUMMARY

In summary, sewage residuals present a challenging matrix for disinfection and stabilization. There are many different stressors that can affect pathogen reduction and other stabilization properties. These stressors are commonly classified as physical, biological, or chemical. All disinfection/ stabilization methods currently in use today use more than one stressor. Many of these methods mix stressors from the three classifications. Optimization of combined stressors can lead to cost reductions and a superior quality biosolids product.

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