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Removal of Triclocarban and Triclosan during Municipal Biosolid Production

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Abstract

The antimicrobial compounds triclosan (TCS) and triclocarban (TCC) accumulate in sludges produced during municipal wastewater treatment and persist through sludge treatment processes into finished biosolids. The objective of this research was to determine the extent to which conventional sludge processing systems such as aerobic digestion, anaerobic digestion, and lime stabilization were able to remove TCC and TCS. Sludge and biosolid samples were collected from 10 municipal wastewater treatment plants in the United States. The concentrations of TCC and TCS in sludge and biosolid samples were determined via heated solvent extraction and analysis with liquid chromatography electrospray ionization mass spectrometry. Dry weight concentrations of TCC and TCS frequently were higher in finished biosolids than in the source sludges because of sludge mass reduction during digestion. The removal of TCC and TCS in municipal biosolid processing systems was determined from the measured concentration change after correcting for reductions in solid mass during sludge treatment. Removal in the digester systems ranged from 15 – 68 % for TCC and 20 – 75 % for TCS. Increased solid retention times during sludge treatment operations were correlated with higher removals of TCC and TCS. Apparent first order degradation rates for TCC ranged from 0.015–0.08 1/d and for TCS were between 0.003–0.15 1/d.

Keywords

biosolids; triclocarban; triclosan; municipal wastewater treatment; land application

Introduction

Trace organic chemicals (TOrcs) including pharmaceuticals, flame retardants, steroids, and hormones, which are often effectively removed from the effluent stream within wastewater treatment plants (WWTPs), have been detected at significant concentrations in sludges and treated sludges, known as biosolids (Chenxi *et al.*, 2008; Joss *et al.*, 2005; Nieto *et al.*, 2010; Ternes *et al.*, 2005). Although WWTPs have to comply with stringent effluent discharge standards, including in many cases target levels for specific organic chemicals, standards for the disposal of sewage sludge are more limited. The EPA 40 CFR 503 rule (503 rule) is a set of criteria and guidelines for municipalities that generate, use, and dispose of sewage sludge. The guidelines include numerical limits for metals and pathogens, vector attraction

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reduction standards, and describe management practices, record keeping and reporting requirements for land applied biosolids and also include similar requirements for sewage sludge that is surface disposed or incinerated (US Environmental Protection Agency, 1994). Currently, municipalities are not responsible for meeting numerical limits for organic pollutants in biosolids. Organic pollutants that were considered during the development of the 503 rule were ultimately not incorporated into the rule because their then-current concentrations did not pose significant risks to human health and the environment and because their production had generally been banned in the U.S. (e.g., polychlorinated biphenyls, organochlorine insecticides). Pharmaceuticals and personal care products, which are the focus of significant current environmental concern, were not considered during the formulation of the 503 rule. These constituents may have negative effects on human health and the environment if released from the biosolids and transported to locations where they can impact human or environmental health. The current concern with TORCs in biosolids suggests that wastewater treatment facilities may eventually be responsible for meeting numeric criteria for trace organic compounds. As a first step in considering potential responses to these concerns, it is essential to know how effectively current WWTP sludge processing operations remove organic pollutants.

The two chemicals selected for this study are the high production volume antimicrobial compounds triclocarban (TCC), N-(4-chlorophenyl)-N'-(3,4-dichlorophenyl)-urea and triclosan (TCS), 2-(2,4-dichlorophenoxy)-5-chlorophenol (Figure 1). TCC and TCS are multi-chlorinated aromatic compounds that are placed in personal care products and common products such as bar soap, toothpaste, liquid soap, cosmetics, and household cleaning products (Adolfsson-Erici *et al.*, 2002; TCC Consortium, 2002; US Environmental Protection Agency, 2008). At typical in – use concentrations both TCC and TCS act as bacteriostats. Research has shown that some bacteria have developed resistance to TCS (Yazdankhah *et al.*, 2006). In vitro testing indicates that TCC can amplify the responses of both the androgen and estrogen receptors when steroidal hormones are present, a unique type of endocrine-disrupting behavior (Ahn *et al.*, 2008). TCS has been detected in soil (McAvoy *et al.*, 2002), fish tissue (Balmer *et al.*, 2003), and human breast milk (Adolfsson-Erici *et al.*, 2002). TCS is also known to be toxic to aquatic biota. Based on these scientific findings, the EPA and FDA are planning to assess the endocrine and toxicological effect of TCS (Orvos *et al.*, 2002).

After use, many products that contain TCC and TCS end up in WWTPs where they can be transformed (e.g., via chemical or biological processes) or physically removed from the aqueous phase (e.g., by volatilization or adsorption to particles or microorganisms that are subsequently removed in settling basins) (Heidler *et al.*, 2006). Previous work supports the idea that significant amounts of TCC and TCS persist through typical unit operations at WWTPs and survive sludge processing operations. Heidler *et al.* (2006) conducted two separate mass balance studies on TCC and TCS at WWTPs. In their studies, they determined the removal efficiencies of TCC and TCS from the liquid–phase of a WWTP were 97% and 98 %, respectively. The majority of TCC and TCS entering the WWTP was removed from the liquid and became adsorbed to the sludge. Wastewater sludge treated in an anaerobic digester for 19 days contained TCC and TCS at concentrations of 51 and 30 mg/kg,

respectively (Heidler and Halden, 2007; Heidler *et al.*, 2006). The US Environmental Protection Agency (EPA) (2009) surveyed sewage sludge from 84 WWTPs subjected to secondary treatment or better for metals and organic pollutants including TCC and TCS. TCC was detected in 100% of the samples with a concentration range of 187 – 441,000 µg/kg. TCS was detected 94 % of the time with a concentration range of 430 – 133,000 µg/kg (US Environmental Protection Agency, 2009). Bester (2003) measured TCS concentrations in final sludges (treated and untreated) from 20 different WWTPs and found that concentrations ranged from 400 – 8800 µg/kg (Bester, 2003). TCC and TCS in biosolids destined for land application may be of concern because the compounds persist in the soils to which they are applied and can bioaccumulate to some degree (Higgins *et al.*, 2010). Although previous studies have examined the removal of these compounds in individual systems (e.g., Poulsen and Bester, 2010, documented TCS removal during thermophilic composting), we are not aware of previous published studies that examine the efficacy of different biosolid treatment processes in removing/degrading TCC and TCS.

The physical-chemical properties of TCC and TCS indicate the reasons that they may be persistent in sludge. Both chemicals are polychlorinated aromatic compounds, which suggest significant resistance to biotransformation and biodegradation (Halden and Paull, 2005). Volatilization is not expected to be a significant removal mechanism for TCC and TCS, which have vapor pressures of 8.9×10^{-3} Pa (Heidler *et al.*, 2006) and 7.0×10^{-4} Pa (Halden and Paull, 2005) and normal boiling points of 344 ± 37 °C at 760 (Halden and Paull, 2004) and >300 (Halden and Paull, 2005). TCC and TCS are also low in water solubility and are lipophilic (Duan *et al.*, 2005; Halden and Paull, 2004). The octanol-water partition coefficients of TCC ($\log K_{ow}=3.5$) (Snyder *et al.*, 2010a) and TCS ($\log K_{ow}=4.8$) suggest a high tendency for sorption to organic matter and particles in sludge (Snyder *et al.*, 2010b; US Environmental Protection Agency, 2008).

Sludge can be treated through various biosolid processing systems to produce a final nutrient-rich organic material known as biosolids. Conventional stabilization systems used to produce biosolids employ anaerobic (mesophilic or thermophilic) or aerobic digestion and/or chemical and thermal stabilization. The most common stabilization system is anaerobic digestion. Previous studies have hypothesized that TCC and TCS resist degradation during anaerobic digestion (Heidler *et al.*, 2006; McAvoy *et al.*, 2002). It has been assumed that TCC will biotransform via reductive dechlorination and TCS via methylation during anaerobic digestion (Heidler and Halden, 2007; Heidler *et al.*, 2006). Another study found that TCC, under aerobic laboratory conditions, degrades into its corresponding chloroanilines (Federle *et al.*, 2002). McAvoy (2002) found that TCS was reduced under aerobic conditions (McAvoy *et al.*, 2002). The aim of this study was to determine the extent to which TCC and TCS were removed from municipal wastewater sludges during biosolid processing. In addition, in the event that some degree of removal was observed, it was also desired to assess whether key operating parameters (e.g., solids residence time) could be related to the degree of treatment/removal.

Experimental Methods

Chemicals

Triclocarban [CAS 101-20-2] and triclosan [CAS 3380-35-5], were purchased from Sigma-Aldrich (St. Louis, MO). Deuterated triclocarban (TCC-d₇) and isotope labeled triclocarban (TCC -¹³C₆) were purchased from Cambridge Isotope Laboratories, Inc. (Andover, MA). Optima LC/MS grade acetone, methanol, and acetonitrile were purchased from Fisher Scientific (Pittsburgh, PA). Deionized water (18 MΩ, MilliQ Water Purification System Millipore, Billerica, MA) was used to prepare all aqueous solutions.

Description of Sample Collection

Potential public and regulatory concerns about trace organic compounds in biosolids motivated anonymous collection of sludge and biosolid samples for this study. Nine WWTPs provided samples to UC Davis Environmental Engineering laboratories via Carollo Engineers (Sacramento, CA). Another WWTP located in Chicago, IL directly submitted sludge and biosolid samples to the laboratories. WWTPs were asked to send samples of their total sludge composition (typically containing primary sludge, waste activated sludge, or a combination) and finished biosolid samples. Seven of the WWTPs employed mesophilic anaerobic digestion, while the remaining three utilized lime stabilization, thermophilic anaerobic digestion, and aerobic digestion. Key characteristics of the treatment train at each plant are summarized in Table 1. All samples were collected between November 2008 and January 2009. Triplicate sub-samples of sludge and biosolid were collected in 500 mL polypropylene wide mouth jars from each WWTP. Plants that operated under continuous conditions collected the sludge at three different time points. Dewatered biosolids for 9 out of the 10 WWTPs were collected at three different locations (e.g., top, middle, and bottom of the pile). The remaining WWTP did not dewater their biosolids, instead the digested biosolids were sent to solid storage basins. Biosolid samples were collected prior to being sent to the basins. Samples were maintained in the dark at < 6 °C from the time of collection until receipt at the laboratory. Samples were subsequently stored at 4°C in the dark.

Sample Preparation and Analysis

All sludge samples were centrifuged for 30 mins at 2794 g to remove excess liquid. A portion of both sludge and biosolid sub – samples was dried in an oven at 70°C for 24 hr and homogenized with a mortar and pestle. Duplicate 1 g sub – samples of the dried material were weighed and placed in 50 mL glass centrifuge tubes. Samples were spiked with 1 mL of 5 mg/L TCC – d₇ in methanol acetone and the solvent was allowed to evaporate under the hood. Samples were extracted via heated shaking at 55°C, 295rpm, for 24 hr in 15 mL of acetone: methanol (50/50 v/v) for TCC and TCS. Following extraction, the samples were centrifuged at 2794 g for 30 mins and filtered with 0.2 μm PTFE 13 mm syringe filters to further remove particulate matter. A 300 μL aliquot of the sample was transferred to an autosampler vial and diluted with 650 μL methanol. 50 μL of 2 μg/mL TCC-⁶C₁₃ (i.e. internal standard) was added to the diluted sample.

LC – MS Analysis

TCC and TCS concentrations were determined by liquid chromatography – mass spectrometry (1100 HPLC and G2445A Ion Trap, Agilent Technologies, Wilmington, DE). The HPLC was equipped with a quaternary pump and refrigerated autosampler. A Phenomenex C18 Prodigy column (5 μ m, 100 Å pore size; 2.0 x 100 mm) with a HPLC security – guard column (2.0 x 4.0 mm) was used at 40°C with an injection volume of 10 μ L. A gradient method consisting of 90:10 deionized water and acetonitrile with 10 mM acetic acid (eluent A) and 50:50 methanol and acetonitrile with 35 mM acetic acid (eluent B) at a constant flow rate of 0.500 mL/min was used with the following gradient profile: 20 to 80 % B, over the first 14.50 min, then ramped to 100% B by 19.00 min, followed by a hold at 100 % B for 1 min, and 20 % B from 20 to 25 min. Compounds were detected and quantified using the ion trap in negative electrospray ionization (ESI) mode. The desolvation gas (N₂) flow, ion gas pressure, and ion temperature were set to 12 mL/min, 35psi, and 350°C, respectively. The MS parameters were optimized for each analyte prior to analysis. A six – point internal calibration curve was generated for each chemical. Quantitative analysis was performed in multiple reaction monitoring (MRM) mode. The criteria used for positive identification of TCC were the retention time (RT \pm 0.1), the parent ion (m/z 313), and transition ion (m/z 160). TCS identification criteria were retention time, the parent ion (m/z 287), and spectra matching. TCC product ion and TCS parent ion were used for quantification. TCC-d₇ (m/z 320 \rightarrow 163) and TCC-⁶C₁₃ (m/z 319 \rightarrow 160) were tracked in the same manner as the analytes of interest. The average spike recoveries for TCC and TCS in sludge were 82.5 % (\pm 9.35 %) and 78.1 % (\pm 11.3 %), respectively. For biosolid samples, the spike recoveries for TCC and TCS were 76.1 (\pm 11.3 %) and 79.8 (\pm 13.6 %), respectively. The measured concentrations were adjusted with the recovered surrogate.

Percent Removal of TCC and TCS

Volatile solids reduction (VSR) occurs during anaerobic and aerobic processes as organic material degrades. Typical ranges for VSR are 40 – 60% for anaerobic digestion and 38 – 50 % for aerobic digestion. VSRs associated with aerobic digestion of a particular waste are typically about 66% of anaerobic digestion VSRs for the same waste (US Environmental Protection Agency, 2003). For constituents that are poorly degraded in these processes, the dry weight constituent concentrations in biosolids are usually higher than those in sludge due to VSR. To account for the VSR that occurs in the biosolid treatment systems, equation 1 was used to calculate adjusted initial TCC and TCS concentrations in sludge.

$$C_{S,ADJ} = \left(\frac{1}{1 - VSR} \right) * C_S \quad \text{Equation 1}$$

VSR is the fractional volatile solid reduction; C_S is the measured concentration of the constituent in sludge (mg/kg dry wt sludge), and C_{S,ADJ} is the adjusted sludge concentration (mg/kg dry wt biosolids). The percent removal was calculated based on the difference between the adjusted sludge concentration and the measured TCC or TCS concentration in the biosolid.

Results and Discussion

The concentration ranges for TCC and TCS in sludge, adjusted to a biosolid dry weight basis, were 8.50 – 69.7 mg/kg and 3.00 – 115 mg/kg, respectively. The adjusted sludge concentration could not be determined for WWTP C, which was the lime stabilization process, because the weight of the sludge increased during stabilization due to the addition of quicklime (i.e. calcium oxide). The initial digester sludge composition in all municipalities consisted of a mixture of primary and secondary sludge. WWTP F, G, and H only provided data for one stream (i.e. primary sludge) instead of their total sludge composition (Table 2). Therefore the total initial concentrations of TCC and TCS in sludge could not be determined for those WWTPs. The concentrations of TCC and TCS entering digester systems have rarely been measured so it is difficult to compare our measurements to previous ones.

Previous studies have hypothesized that the majority of the TCC and TCS entering WWTPs sorb to particulate matter and microorganisms and settle in the primary clarifier with only a small amount making it to secondary treatment (Heidler and Halden, 2007; Heidler *et al.*, 2006; Winkler *et al.*, 2007; Ying *et al.*, 2007). WWTP C and I were the only plants that provided individual samples from their primary and waste activated sludge streams. The secondary treatment system at WWTP C consisted of a trickling filter with solid contact (TF/SC) while the secondary treatment at WWTP I was a pure oxygen activated sludge system. The concentrations of TCC and TCS were higher in the waste activated sludge (34.7 mg/kg TCC and 28.2 mg/kg TCS) than in the primary sludge (16.3 mg/kg TCC and 17.3 mg/kg TCS) for WWTP C. The results were opposite for WWTP I with primary sludge concentrations (10.8 mg/kg TCC and 15.5 mg/kg TCS) higher than those in the waste activated sludge (2.71 mg/kg TCC and 3.26 mg/kg TCS). The two systems had very similar concentrations of TCC and TCS in their primary sludges, suggesting the influents to these systems contained similar ratios of these chemicals to settleable solids. The significant difference between the systems in TCC and TCS concentrations in sludges from the secondary clarifiers likely relates to the much lower suspended solid concentrations and shorter mean cell residence times typical of TF/SC processes, which often have MCRT in the aeration basin of ~1 hr (compared with the reported 2.65 d MCRT at WWTP I). Higher MCRTs, achieved by exposing each particle to larger volumes of water, allow for the accumulation of higher concentrations of hydrophobic chemicals like TCC and TCS in the solids before they are wasted. We suspect that a larger database of secondary sludge compositions would reveal, on average, a trend toward higher sludge concentrations of TCC, TCS and other hydrophobic chemicals with increased MCRT.

The concentrations of TCC and TCS in finished biosolids were measured for all WWTPs. The concentration ranges of antimicrobial compounds in biosolids were 6.05 – 24.6 mg/kg for TCC with an average concentration of 16.2 mg/kg, and 1.56 – 32.3 mg/kg for TCS with an average concentration of 20.4 mg/kg (Figure 2). The concentration ranges of TCC and TCS measured here are within the ranges observed in the national sewage sludge survey by US EPA with the average values within 0.5 standard deviations of the averages in the EPA study (US Environmental Protection Agency, 2009). One difference between this study and previous studies are that TCS concentrations in biosolids were, on average, higher than TCC

concentrations, and this pattern was found at 8 of the 10 facilities (Heidler and Halden, 2007; Heidler *et al.*, 2006; US Environmental Protection Agency, 2009). It is unclear whether this difference is caused by regional variation in TCC and TCS consumption patterns or treatment related factors. Treatment factors may have played a role at WWTP C, in particular, because the high pH produced by lime stabilization processes is likely to increase the efficiency of extraction of TCS, which is predominantly ionized and consequently more soluble and more likely to be desorbed at pH values above its pK_a of 7.9.

The efficiency of TCC and TCS removal was calculated by comparing adjusted sludge concentrations to biosolid concentrations for all systems except WWTPs C, F, G, and H, which were excluded for reasons stated earlier. The biosolid digestion systems removed 15 – 68 % of TCC and 20 – 75 % of TCS. Within this limited sample, mesophilic anaerobic digestion processes removed the highest percentage of TCC and TCS. As previously mentioned reductive dechlorination is a potentially important form of transformation for TCC under anaerobic conditions while conversion of TCS to methyl TCS in thermophilic composting has been documented (Miller *et al.*, 2008; Poulsen and Bester, 2010). The present study provides the first indication that longer solid residence times in sludge treatment operations are associated with more significant transformation of TCC and TCS; anaerobic digesters with longer SRT had a greater percent removal of TCC and TCS (Figure 3). It is typical for anaerobic digesters, especially mesophilic, to have longer digestion times than other biosolid digestion systems. Previous studies have suggested that little removal/degradation occurred for TCC and TCS under anaerobic conditions but those studies explored only one anaerobic digestion system with a SRT of 19 days (Heidler and Halden, 2007; Heidler *et al.*, 2006). McAvoy (2002) showed little removal of TCS during anaerobic digestion but the SRT of the system was not stated. WWTP I was the only plant that showed no significant removal of TCC and TCS but that plant also had the shortest SRT (i.e. 15 days) of the anaerobic digesters examined here (McAvoy *et al.*, 2002). EPA (2010) found that better removal of endocrine disrupting chemicals occurred with longer sludge retention time (US Environmental Protection Agency, 2010).

Even though the one aerobic digestion system included in our study had the shortest SRT, the system removed a significant percentage of TCC and TCS. Previous bench scale studies indicated that aerobic treatment was better than anaerobic treatment for the removal of TCC and TCS (Gledhill, 1975; McAvoy *et al.*, 2002). This study suggests that an aerobic degradation process may remove TCC and TCS more effectively than an anaerobic process with a longer SRT. Examination of TCC and TCS removal in aerobic digestion processes with varying SRTs needs to be performed to determine whether this process is systematically more effective than anaerobic systems with similar SRT values.

Removal Rate and Half Life

The degradation data in Figure 2 were combined with the solid residence times in each system to estimate the half lives of TCC and TCS in the treatment systems studied here (Table 3). Estimates of first order degradation rate constants (k) and half lives ($t_{1/2}$) were calculated according to:

$$k = \frac{1}{SRT} \ln \left(\frac{C_B}{C_{S,ADJ}} \right) \quad \text{Equation 2}$$

$$t_{\frac{1}{2}} = \frac{0.693}{k} \quad \text{Equation 3}$$

where C_B is the concentration of TCC or TCS in the finished biosolid and the other terms are as previously defined. First order kinetics does not take into account factors (i.e. microbial population, interference of other contaminants, dispersion) that may influence the rate of degradation of chemicals in a digestion system (Bekins *et al.*, 1998). However, to facilitate comparison with results from previous research on TCC and TCS degradation in compost, soil, and soils amended with biosolids, it was assumed first order kinetics occurred within the digester.

The calculated half lives ranged from 8–46 d for TCC and 4–24 d for TCS for WWTPs A, B, D, E, and J. WWTP I had distinctly different results with an undefined half-life for TCC using equations 2 and 3 and a calculated half-life for TCS of 210 d. The results showed a general trend toward decreased half-life with increasing SRT (Table 3). Although the differences were not large, TCC had lower transformation rate constants than TCS and longer half-lives in all of the digestion systems, which is consistent with previous research. Although the chemicals have similar physical – chemical properties, the hydroxyl group in TCS is more likely to undergo transformation while the urea group in TCC is more resistant to transformation (Heidler *et al.*, 2006; National Industrial Chemicals Notification and Assessment Scheme, 2009). The estimated half lives in the sludge treatment systems were generally lower than the studies that examined the degradation rates of TCC and TCS in soils and biosolid amended soils (Lozano *et al.*, 2010; Waria *et al.*, 2011; Ying *et al.*, 2007). However, the half-life measured for TCS in a composting system was similar to the results of this study (Poulsen and Bester, 2010; Ying *et al.*, 2007). Although all these systems were under aerobic conditions factors such as the variation of microbial population and concentration, organic carbon content, and pH, affected the degradation rates of TCC and TCS.

Conclusions

Aerobic and anaerobic digestion systems at municipal wastewater treatment plants removed substantial fractions of the TCC and TCS in the entering sludges, but the significant residual concentrations observed were consistent with those determined in previous research. The elevated residual concentrations presumably result from the high input mass loads of TCC and TCS resulting from their widespread use in consumer products. Measured half-lives of the compounds of 4–46 d suggest that it will be impractical to achieve >90% degradation of the compounds in conventional sludge treatment systems. TCS was more rapidly removed than TCC, consistent with previous research indicating that TCS is more readily biotransformed than TCC. This research did not determine if TCC and TCS was mineralized (i.e. converted to CO_2 , H_2O , NH_4^+) or biotransformed during the digestion process. The transformation by - products of TCC and TCS produced during digestion need to be further

researched to determine if they pose greater risks to human health and the environment compared with the parent compounds.

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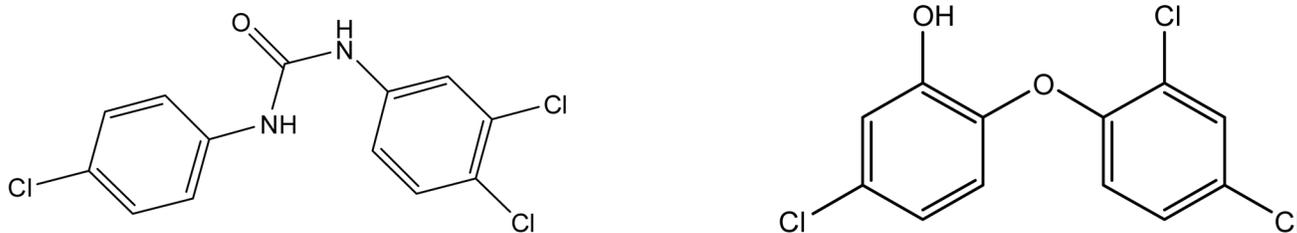


Figure 1.
Chemical Structures of triclocarban (TCC; left) and triclosan (TCS; right)

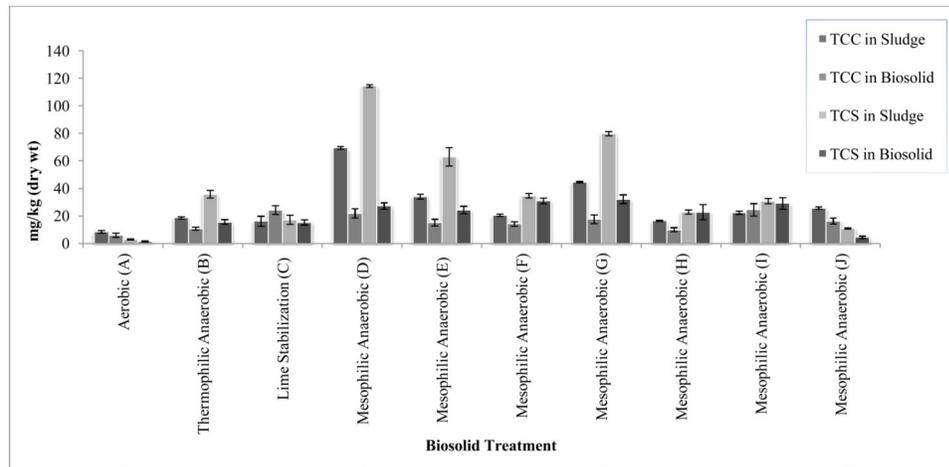


Figure 2.

Concentrations of TCC and TCS in municipal sludge and biosolids; Error bars indicated the standard deviation of 2 replicate samples from three different sampling locations; n = 6.

*WWTP C, F, G and H sludge concentrations were not adjusted for volatile solid reduction.

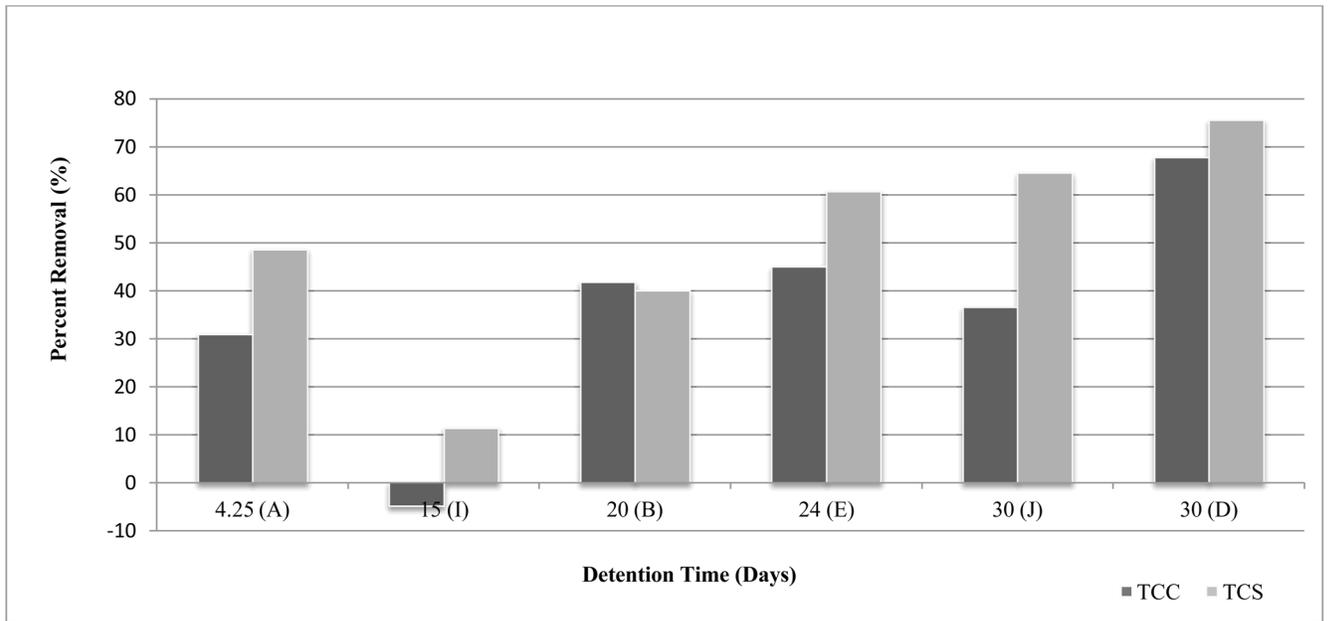


Figure 3.
Percent removal of TCC and TCS vs Solid Residence Time.

Table 1

Wastewater treatment plants descriptions.

Agency	Flow		Primary	Secondary			Thickening			Digestion				Dewatering		Comments
	MGD	Residential (%)		Attached Growth	Type	BNR	MCRT (days)	GBT	DAFT	Other	MA ¹	TA ²	Aerobic	Detention Time (days)	Belt Press	
A	0-10	95	X			8.5			X			X	4.25	X		
B	0-10	99	X		X	11		X	X		X		20	X		Has algae DAFT as well
C	10-20	90	X	TF/SC			X							X	X	Lime stabilization of biosolids
D	20-100	95	X	X		1	X	X		X			25-30		X	Screw Press
E	10-20	95	X			8.9	X			X			24	X		
F	20-100	80	X	Portion		1		X		X			18	X		
G	>100	80	X			1		X		X			20	X		
H	10-20	97	X			3	X			X			20-30	X		
I	>100	87	X			2.65	X	X		X			15			
J	>100		X							X			30			

¹MA - Mesophilic anaerobic

²TA - Thermophilic anaerobic

Table 2

Digester sludge composition and volatile solid reduction.

WWTP	Primary Sludge/Waste Activate Sludge	VSR (%) ¹
Aerobic (A)	10/90	39
Thermophilic Anaerobic (B)	19PS/69WAS/12AD ²	55
Lime Stabilization (C)	72/28	N/A ³
Mesophilic Anaerobic (D)	54/46	59
Mesophilic Anaerobic (E)	71/29	56
Mesophilic Anaerobic (F) ⁴	78/22	55
Mesophilic Anaerobic (G) ⁴	72/28	64
Mesophilic Anaerobic (H) ⁴	70/30	51
Mesophilic Anaerobic (I)	70/30	63
Mesophilic Anaerobic (J)	40/60	50

¹ Volatile solid reduction provided by each WWTP; recorded at time of collection

² AD is algae daft stream, assumed it was an inert material

³ Volatile solid reduction did not occur during that process

⁴ Only primary sludge collected; could not determine the initial concentration of TCC and TCS in sludge going into the digester

Table 3

Apparent first order rate constants and half lives for TCC and TCS under various conditions.

Source	Detention Time (days)	Apparent first order k (1/day) TCC	Half life TCC (days)	Apparent first order k (1/day) TCS	Half life TCS (days)	Reference
Loam soil under aerobic conditions	70	0.00642	108	0.0385	18	(Ying <i>et al.</i> , 2007)
Compost ¹	24	N/A ²	N/A	0.0280	25.0	(Poulsen and Bester, 2010)
Land Applied Biosolids ³	487	N/A	N/A	0.00645 ⁴	108	(Lozano <i>et al.</i> , 2010)
Biosolid amended w/fine sand soil	126	N/A	N/A	-0.00056	1243	(Waria <i>et al.</i> , 2011)
Biosolid amended w/silty clay loam soil	126	N/A	N/A	-0.00516	134	(Waria <i>et al.</i> , 2011)
Aerobic Biosolid (A)	4.25	0.0800	8.66	0.153	4.53	Present Study
Mesophilic Anaerobic Biosolid (I)	15	NR ⁵	NR	0.00330	210	Present Study
Thermophilic Anaerobic Biosolid (B)	20	0.0269	25.8	0.0414	16.7	Present Study
Mesophilic Anaerobic Biosolid (E)	24	0.0399	17.4	0.0472	14.7	Present Study
Mesophilic Anaerobic Biosolid (J)	30	0.0151	46.0	0.0291	23.8	Present Study
Mesophilic Anaerobic Biosolid (D)	30	0.0384	18.1	0.0476	14.6	Present Study

¹ 42% digested sewage sludge, 30% yard and park waste, 12% straw/horse manure, 7% card board, yard and park waste, 12% straw/horse manure, 7% card board, and 9% Troltex ((insulation material containing wood shavings and cement) by weight

² Not Available

³ Range of single application rate 14.3 – 25 tons ha⁻¹

⁴ Rate constant and half were estimated

⁵ No Removal of contaminant