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Review

Sustainable approaches for minimizing biosolids production and maximizing reuse options in sludge management: A review

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ABSTRACT

Sludge generation during wastewater treatment is inevitable even with proper management and treatment. Yet proper handling and disposal of sludge are still challenging in terms of treatment cost, presence of recalcitrant contaminants of concern, sanitary issues, and public acceptance. Conventional disposal methods (i.e. landfilling, incineration) have created concerns in terms of legislative restrictions and community perception, incentivizing consideration of substitute sludge management options. Furthermore, with proper treatment, biosolids from sludge, rich in organic materials and nutrients, could be utilizable as fertilizer. Despite the challenges of dealing with sludge, no review has dealt with integrated source reduction and reuse as the best sustainable management practices for sludge treatment. In this review, we present two main approaches as potentially sustainable controls: (i) pretreatment for minimizing extensive sludge treatment, and (ii) recycling and reuse of residual sludge. Drawing on these approaches, we also suggest strategies for efficient pretreatment mechanisms and residual reuse, presenting ideas for prospective future research.

1. Introduction

Sludge produced from wastewater treatment processes consists of various substances including organics, nutrients, and pathogens, most affecting public health and the environment (Werther and Ogada, 1999; Wang et al., 2008; Roy et al., 2011). The activated sludge process, which yields sludge, is commonly employed at wastewater treatment plants globally (Boehler and Siegrist, 2006). Due to foul odor, presence of pathogens, and large volume produced, proper disposal has been problematic (Werther and Ogada, 1999; Aldin et al., 2011; Fytili and Zabaniotou, 2008). While conventional treatments such as landfilling, incineration, or land application (Brisolara and Qi, 2013) could be operated conveniently and economically, these treatments have faced significant hurdles (i.e. legislative forces and public perception).

As examples, construction and operation of landfills have been restricted due to legislation in many countries (Boehler and Siegrist, 2006; Werle and Wilk, 2010; Fytili and Zabaniotou, 2008), and due to leachates containing heavy metals (Fytili and Zabaniotou, 2008; Singh and Agrawal, 2008), despite having provided technologically simple means of biosolid disposal for many decades. Landfilling, one of the conventional treatment options, encounters issues of public acceptability and greenhouse gas emissions (Wang et al., 2008), contributing to difficulties in landfill construction and operation. Furthermore, landfill leachate from runoff poses risks to the environment, contaminating groundwater and soil.

Land application, similar to landfilling except typically having other uses (often agricultural) for the land application area (Brisolara and Qi, 2013), provides an alternative for biosolids disposal. However, a direct channel between biosolids and agricultural production has been problematic due to contaminants such as carcinogenic organics and heavy metals contaminating soil and crops (Clarke and Cummins, 2015; Cincinelli et al., 2012; Singh and Agrawal, 2008), and due as well to soil worms bioaccumulating contaminants from sludge (Elissen et al., 2010). Likewise, runoff from land application causes the same leachate issues present at landfills. Land application is thus not considered to be a sustainable option for sludge disposal.

Incineration, as an alternative to landfilling and land application, and widespread in many densely populated areas, could offer

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significant volume reduction (Roy et al., 2011; Werther and Ogada, 1999; Li et al., 2014). However, due to high energy consumption caused by high moisture content and low heating value of biosolids (Wang et al., 2008), additional fuel is required for maintenance of incineration facilities. In addition, ash produced from incineration contains hazardous substances (Donatello et al., 2010) and substantial air emissions from sludge incinerators also contribute to various greenhouse gases (Murakami et al., 2009). Thus, despite achieving substantial volume reduction, incineration faces challenges similar to the previously mentioned conventional methods of dealing with sludge.

Thus, typical sludge disposal methods confront issues of social, environmental, and economic concern, encouraging the development of alternative treatments to overcome such barriers. Approaches should be aimed at minimizing sludge disposal, such that upon source reduction, residual biosolids are available for beneficial reuse. In short, sustainable sludge management should seek source reduction, followed by residual reuse.

Recent studies have focused on performance enhancement of specific unit reactors (i.e. the upflow anaerobic sludge blanket) for sludge disposal, sludge minimization by in-situ activated sludge treatment, removal of emerging contaminants by combined pretreatment and biotransformation, sludge treatment wetlands, water quality and management from biosolids application, biosolids effects on nutrients buildup in soils, and effects of biosolids application on transport of contaminants in soils (Chong et al., 2012; Wu et al., 2012; Uggetti et al., 2010; Barnabé et al., 2009; Guo et al., 2013; Borgman and Chefetz, 2013; Elliott and O'Connor, 2007; Qiong et al., 2012; McFarland et al., 2012). Searching more than 500 recent references, we find few that examine fundamental, sustainable approaches to source reduction or options for beneficial reuse of biosolids.

In our review, we describe the state of the art in source reduction and beneficial reuse techniques for wastewater treatment plant residuals. Source reduction techniques such as thermal, chemical, electromagnetic, ultrasonic, microwave, and mechanical treatments are reviewed, including reasons for their selection and their benefits in comparison to other methods. Methods for best management practices are considered in terms of both performance and implementation feasibility in real-world applications.

Options for reuse of residual biosolids are discussed along with performance-based characteristics. While innovative methods for reducing sludge production are important, we envisage that designing pretreatment to not only minimize sludge but also to remove hazardous substances would offer substantial advantages compared to dealing with sludge disposal at the final stage. Special attention is paid to the applicability of such technologies for retrofit applications, as it is envisioned that this will be a large future market for improvements in biosolids management. Implemented together, the approaches to source reduction and beneficial reuse reviewed will address the social, environmental, and other challenges facing current sludge disposal methods.

2. Source reduction

As one aspect of sustainable approaches, waste sludge should be minimized prior to further treatment or reuse of biosolids. Sludge treatment practices have emphasized the decomposition of organic materials by bacteria during digestion. While ultimate products from consumption of organics by bacteria vary (i.e. CO_2 or methane in aerobic or anaerobic digestion), increasing the rate and extent of digestion clearly reduces the final residual volume. For digestion, the availability of organics to bacteria is critical in the aqueous sludge matrix, yet most organics are within cells or complex macromolecules and not readily accessible to bacteria. Thus, sludge pretreatment centers on the hydrolysis or physical destruction of cells within the sludge, releasing organics to the aqueous environment. In assessing pretreatment effectiveness, three indicators (degree of solubilization, extent of disintegration, increase in biogas production) are compared for the pretreatment techniques discussed below.

2.1. Chemical pretreatment

Chemical pretreatment through hydrolysis and disintegration of complex macromolecules in sludge is a common technique utilized to enhance biogas production (Shi et al., 2015; Zhang, 2010). Alkaline addition (i.e. NaOH) as part of integrated chemical pretreatment indicated encouraging results in enhancing sludge disintegration and increasing biogas production (Xu et al., 2014; Fang et al., 2014; Şahinkaya and Sevimli, 2013; Shao et al., 2012; Jin et al., 2009; Chi et al., 2011).

The degree of disintegration may depend on alkaline doses and types of sludge. For instance, Li et al. (2012) carried out a series of continuously stirred batch reactor experiments with doses from 0.1 to 0.5 mol/L NaOH and 30 min contact time. The extent of disintegration was as high as 26.9% with a 0.1 mol/L dose for a sample consisting of an 80%/20% mixture of primary and biofilm sludges. However, the same pretreatment process achieved disintegration rates between 40% and 52% for waste activated sludge (WAS) containing a greater concentration of organics (Li et al., 2008; Fang et al., 2014).

On the other hand, a delay in biogas production could occur due to alkaline pH conditions, and the magnitude of the delay, between one and three days, increased with the chemical dose utilized (Li et al., 2012). Such results suggest that alkaline pretreatment could effectively enhance the amount of soluble chemical oxygen demand (SCOD) and total biogas production. While the digestibility of sludge was increased with NaOH pretreatment, low treatment efficiency was observed for primary sludge (Li et al., 2012), indicating that the type of sludge influences chemical pretreatment performance. Alkaline pretreatment offers comparative operational advantages in retrofit or other space-limited project sites in terms of simple equipment (i.e. chemical injection pumps), small footprint, and low energy consumption (Neyens et al., 2003; Kim et al., 2010).

With operational convenience (i.e. on-site generation) and minimum resource requirements (i.e. electricity, air), ozonation is another chemical pretreatment applied to sludge. Ozone doses required per gram of sludge total suspended solids (TSS) range from 0.025 to 1.2 g (Chu et al., 2008). Boehler and Siegrist (2007) found that ozonation operation at utility-scale wastewater treatment plant facilities resulted in sludge volume reduction of 30% for secondary sludge, but they did not discuss degree of disintegration (DD) or increase of SCOD.

At the pilot scale, Lee et al. (2005) reported 30% solubilization operating in batch mode with 0.05 g ozone per gram of TSS. Despite the modest solubilization performance, Ak et al. (2013) noted a 100% increase in biogas production with a dose of 2.65 mg ozone per gram of sludge biomass, again at the bench scale. Chu et al. (2009) found that ozonation performance was improved by utilizing a microbubble ozone delivery system, with 40% solubilization at the bench scale; no information on pilot or utility-scale implementation of the microbubble system was given. Since the total ozone dose was relatively high, at 0.16 g ozone per gram TSS, it is unclear whether the improvement in performance is due to the use of the microbubble system or to the greater ozone dose.

Ultimately, there is a dearth of data on implementation of ozonation for sludge pretreatment at utility-scale plants. With high energy consumption a potential challenge of ozonation, alkaline pretreatment with NaOH appears to be the most advantageous of