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Sludge disinfection using electrical thermal treatment: The role of ohmic heating

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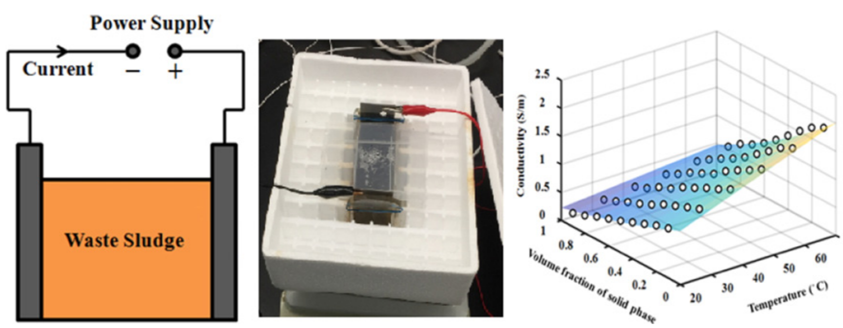
HIGHLIGHTS

- The relationship of ohmic heating and sludge condition was investigated.
- Solid fraction and conductivity are two critical factors for heat production.
- Heat production in sludge was successfully predicted using theoretical models.
- AC power is more effective to heat sludge than DC power.
- Ohmic heating is energy efficient for decentralized sludge disinfection.

GRAPHICAL ABSTRACT



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ABSTRACT

Electrical heating has been proposed as a potential method for pathogen inactivation in human waste sludge, especially in decentralized wastewater treatment systems. In this study, we investigated the heat production and *E. coli* inactivation in wastewater sludge using electrical thermal treatment. Various concentrations of NaCl and NH_4Cl were tested as electrolyte to enhance conductivity in sludge mixtures. At same voltage input (18 V), sludge treated with direct current (DC) exhibited slower ascent of temperature and lower energy efficiencies for heat production comparing to that using alternate current (AC). However, DC power showed better performance in *E. coli* inactivation due to electrochemical inactivation in addition to thermal inactivation. Greater than $6\log_{10}$ removal of *E. coli* was demonstrated within 2 h using 0.15 M of NaCl as electrolyte by AC or DC power. The heat production in sludge was modeled using Maxwell–Eucken and effective medium theory based on the effective electrical conductivity in the two-phase (liquid and solid) sludge mixtures. The results showed that the water and heat loss is a critical consideration in modeling of sludge temperature using ohmic heating. The experimental data also suggested that the models are less applicable to DC power because the electrochemical reactions triggered by DC reduce the concentration of NH_4^+ and other ions that serve as electrolyte. The results of this study contribute to the development of engineering strategies for human waste sludge management.

Abbreviations: AC, alternate current; DC, direct current; DI, deionized water; EEC, effective electrical conductivity; EMT, effective medium theory; EPA, environmental protection agency; LB, Luria-Bertani; ME, Maxwell–Eucken; MPN, most probable number; OH, ohmic heating; PBS, phosphate buffer saline; RMSD, root mean squared deviation.

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1. Introduction

Worldwide, 2.7 billion people rely on onsite sanitation. Yet, there is still no adequate management system in place to deal with the resulting fecal sludge. The Reinvent the Toilet Challenge initiated by Bill and Melinda Gates Foundation in 2011 has effectively promoted the creation of a toilet that removes germs from human waste; operates without connections to water, sewer or electrical lines; and promotes sustainable and financial profitable sanitation services. The solar toilet developed by California Institute of Technology emerged as a promising technology that has demonstrated efficiency and reliability in both lab-scale and field-scale operation to removal human pathogens from wastewater (Huang et al., 2016; CalTech News). The technology relies on electrochemical oxidation of organics and pathogens in the outflow of waste settling tank to generate treated water for reuse in toilet flushing. However, the current technology is not suitable for waste sludge treatment in the storage tank due to the high concentration of organics and associated energy demand for their removal.

Direct disposal of waste sludge, even after partial digestion, contaminates water and soil with high loads of human pathogens (Sidhu and Toze, 2009; Guzman et al., 2007). Diarrheal diseases and soil-transmitted helminthes infections are common occurrence among children in developing countries and are significant burdens to quality and expectancy of life. On the other hand, the nutrients and biomass contained in waste sludge could potentially be useful for enhancing agriculture production (Lu et al., 2012; Mateo-Sagasta et al., 2015). Sludge application to land as soil amendments or fertilizers is commonly practiced in many countries (Lowman et al., 2013; Yang et al., 2015; Pritchard et al., 2010; Lyberatos et al., 2011), yet often without the proper consideration of human health risk from exposure to pathogens.

In the developed country such as United States, pathogen inactivation is mandated prior to sludge disposal or land application (U.S. Environmental Protection Agency, 2003). A number of treatment methods have been authorized by the US EPA for sludge management, including composting, lime stabilization, aerobic digestion and anaerobic digestion. Aerobic digestion and anaerobic digestion are perhaps the most common methods for on-site treatment systems, but disinfection of pathogens is very slow in such processes. For example, it may take 60 days to reduce bacterial and viral pathogens at room temperature, while parasites such as helminthes ova may still be active after treatment (U.S. Environmental Protection Agency, 2003). Disinfection methods such as chlorination, radiation or ozonation that are commonly applied to wastewater effluent are not suitable for sludge treatment. Development of effective technology for onsite sludge disinfection is therefore necessary and urgent.

Ohmic heating (OH), an electrical thermal treatment, may have the potential to serve as the technology for onsite sludge disinfection. OH is produced by electric current passing through materials. It has a long and successful history of application in the food industry for food sterilization (Chen and Mujumdar, 2002; Tuan et al., 2012; Zhan et al., 2015; Daneshmand et al., 2012) and is more recently proposed for disinfection of sewage sludge (Takhtehfouladi et al., 2013, 2015). Comparing to traditional external heating processes, OH can rapidly and uniformly increase the temperature of target material without the need of heat transfer between the solid-liquid interface because heat is produced within the material (de Alwis and Fryer, 1992; Knirsch et al., 2010; Sastry and Barach, 2000; Sakr and Liu, 2014). Temperature is considered as a key measure in pathogen inactivation during OH processes, and it is positively related to the effective electrical conductivity (EEC) of the target specimen (Sastry and Palaniappan, 1992; Palaniappan and Sastry, 1991).

Determination of EEC in a multi-phase mixture (i.e. chicken soup or waste sludge) is perhaps the most important but challenging step in understanding the electrical treatment efficiency. Comparison of several previously published models for EEC (Mahmoud et al., 2011; Han and Choi, 1998) indicates that Maxwell–Eucken (ME) and effective medium theory (EMT) model are the best accepted models for predicting EEC of two-phase food mixture during OH treatment (Perez and Calvelo, 1984; Zhu et al., 2010). The ME model considers the mixture as a heterogeneous medium that contains one or more dispersed phases embedded in a continuous phase (Pietrak and Wisniewski, 2015; Wang et al., 2008). It usually includes two forms: 1) liquid phase serves as the continuous phase in ME-1 model; and 2) solid phase serves as the continuous phase in ME-2 model. By contrast, the EMT model is used to estimate the EEC when there is no obvious dispersed phase or continuous phase. It is a generalized model with the assumption that all phases in a heterogeneous medium are randomly distributed and mutually dispersed (Wang et al., 2006; Wang et al., 2008). Neither model has been applied to electrical heating in sludge treatment to predict thermal conductivity and heat production.

In the past, applications of electric field in sludge treatment mainly focused on sludge dewatering (Glendinning et al., 2009; Mahmoud et al., 2010; Tuan et al., 2012; Citeau et al., 2012). By applying direct current (DC) through sludge, water is separated from sludge particles by electro-osmotic force with relatively low energy consumption (Zhan et al., 2015; Esmaeily et al., 2006; Habel, 2010; Huang et al., 2008; Navab-Daneshmand et al., 2012). OH can enhance the electro-dewatering processes by increasing the sludge temperature, evaporation and electro-osmotic flow (Mahmoud et al., 2011; Mahmoud et al., 2016; Navab-Daneshmand et al., 2015). Recently, a Bioelectro technology was proposed for sludge/biosolid disinfection, in which OH was implied in the heat production (Takhtehfouladi et al., 2013; Takhtehfouladi et al., 2015). Sludge temperature reached 95 °C within a few hours at an applied voltage gradient of <5 V/cm (Takhtehfouladi et al., 2013). Electric conditioners, such as ammonia salts were added to increase conductivity of sludge mixture and promote heat production (Esmaeily et al., 2006; Safaei et al., 2009). The reliable performance in inactivating a wide range of microorganisms in sludge through electrical heating process was demonstrated and was proposed as sustainable approach for waste sludge management (Esmaeily et al., 2006; Habel, 2010; Huang et al., 2008; Takhtehfouladi, 2007; Takhtehfouladi et al., 2013).

Navab-Daneshmand et al. (2012) suggested that OH was the primary mechanism for microbial inactivation in biosolids during electro-dewatering treatment. Other studies demonstrated that the formation of chemical byproducts, such as chlorine or H_2O_2 during electric thermal treatment facilitated pathogen removal (Huang et al., 2016; Habel, 2010; Li et al., 2004). The contribution of these inactivation mechanisms at different operational conditions needs to be further investigated and clarified. Furthermore, the heat production and energy consumption vary with volume fraction of solid sludge, the concentration of inorganic and organic salts in the sludge mixture and type of current (AC vs. DC) applied (Zhang et al., 2017; Habel, 2010; Esmaeily et al., 2006; Takhtehfouladi, 2012). The operational parameters of the electrical thermal treatment should be carefully designed, controlled and optimized in order to reach energy efficiency and complete inactivation of pathogens. The objectives of this study are to: 1) compare and optimize the operational parameters, including different power supplies and salt concentrations, to achieve energy efficiency and pathogen removal in sludge treatment; 2) validate the ME and MET model in predicting the effective electrical conductivity of sludge; 3) develop a mathematical model to predict the heat production and temperature increase during the OH treatment. The study presented here offers mechanism understanding of heat production during OH and presents strategies for design optimization for enhancing the sludge treatment efficiency.

2. Material and methods

2.1. Sludge sampling and preparation

Secondary (returned) activated sludge was collected from Orange County Sanitation District (Fountain Valley, CA). The plant represents