Journal of Environmental Management 184 (2016) 575–584

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Microwave treatment of faecal sludge from intensively used toilets in the slums of Nairobi, Kenya

Peter M. Mawioo [a,*], Christine M. Hooijmans [a], Hector A. Garcia [a], Damir Brdjanovic [a,b]

[a] Department of Environmental Engineering and Water Technology, UNESCO-IHE Institute for Water Education, Westvest 7, 2611 AX Delft, The Netherlands
[b] Department of Biotechnology, Delft University of Technology, Julianalaan 67, 2628 BC Delft, The Netherlands

ARTICLE INFO

Article history:
Received 3 June 2016
Received in revised form
10 October 2016
Accepted 12 October 2016
Available online 23 October 2016

Keywords:
Emergency sanitation
Faecal sludge
Microwave treatment
E. coli and Ascaris reduction
Volume reduction

ABSTRACT

Toilet facilities in highly dense areas such as the slum and emergency settlements fill up rapidly; thus, requiring frequent emptying. Consequently, big quantities of fresh faecal sludge (FS) containing large amounts of pathogens are generated. Fast and efficient FS treatment technologies are therefore required for safe treatment and disposal of the FS in such conditions. This study explores the applicability of a microwave (MW) technology for the treatment of fresh FS obtained from urine-diverting dry toilets placed in slum settlements in Nairobi, Kenya. Two sample fractions containing 100 g and 200 g of FS were exposed to MW irradiation at three input MW power levels of 465, 1085 and 1550 W at different exposure times ranging from 0.5 to 14 min. The variation in the FS temperature, pathogen reduction via the destruction of *E. coli* and *Ascaris lumbricoides* eggs, and vol/wt reduction were measured during the MW treatment. It was demonstrated that the MW technology can rapidly and efficiently achieve complete reduction of *E. coli* and *Ascaris lumbricoides* eggs, and over 70% vol/wt reduction in the fresh FS. Furthermore, the successful evaluation of the MW technology under real field conditions demonstrated that MW irradiation can be applied for rapid treatment of fresh FS in situations such as urban slum and emergency conditions.

1. Introduction

Sanitation facilities, especially the toilets provided in densely populated areas, such as urban slums and emergency settlements, fill up fast due to intensive use and they require frequent emptying. For instance, Sanergy, a social enterprise, empties fresh faecal sludge (FS) from over 700 toilet units that serve over 30,000 users daily in the informal settlements of Nairobi, Kenya (Sanergy, personal communication). Also, approximately 50–200 users per toilet per day are commonly observed in disaster situations (The Sphere Project, 2011); especially, at the onset of emergencies (UNHCR, personal communication). Consequently, large quantities of fresh FS are generated which require safe treatment and disposal. Various issues are identified that generally present a challenge to the FS management, especially in densely populated conditions. FS contains high amounts of pathogens such as bacteria, helminths, viruses, protozoa, and others (Fidjeland et al., 2013; Jimenez et al., 2006; Richard, 2001), which can pose a great risk to the public heath if it is inappropriately managed. In addition, the large amount of emptied fresh FS may need to be transferred to disposal sites far away from the points of generation, as in slum and emergency settlements where land space constraints and lack of adequate disposal possibilities are common. Massive expenditure may thus be incurred in emptying and transporting large amounts of FS, which would make the operation and maintenance of the sanitation system overly expensive. An example is the Haiti emergency camps six months after the 2010 earthquake, where a relief agency (Action Contre la Faim (ACF)) still incurred a monthly expenditure of approximately USD 500,000 to empty the toilets and dispose of FS (Bastable and Lamb, 2012). FS also contains high amounts of organic matter whose uncontrolled degradation in the environment can result in the generation of offensive odour, which may cause respiratory-related complications and attract disease vectors. These concerns form a major challenge to FS management in densely populated areas; hence requiring solutions that are more adapted to those conditions. The common sanitation solutions provided in urban slum and emergency settlements are mainly containment options. These comprise a range of onsite toilet facilities including chemical toilets, packet toilets (e.g. peepoo and wagbag), bucket latrines or elevated toilets, trench latrines, pit

* Corresponding author.
E-mail address: p.mawioo@unesco-ihe.org (P.M. Mawioo).

http://dx.doi.org/10.1016/j.jenvman.2016.10.019

latrines, and others (Harvey, 2007; Katukiza et al., 2012). In recent years, there have also been remarkable efforts to expand the onsite toilet options in which a number of prototypes have been developed. However, parallel efforts to develop technology options to treat FS generated from those toilets still have to be demonstrated in practice.

Various treatment alternatives are available for FS such as composting, co-composting with organic solid waste, conventional drying (e.g. in sludge drying beds), anaerobic co-digestion with organic solid waste, and co-treatment in wastewater treatment plants (Ingallinella et al., 2002; Katukiza et al., 2012; Ronteltap et al., 2014). However, they are mostly suited for regular sanitation contexts and have limitations such as slow treatment processes, large land space requirements, among others (Mawioo et al., 2016), which hinder their application to situations with unusually high rate of FS generation. Consequently, there is need to develop FS treatment technologies that are more appropriate for conditions such as those prevailing in slums and emergencies. Key among the desired characteristics for an appropriate FS treatment technology in these situations is that it should be fast, efficient, and compact for easy and rapid deployment. Particularly, the technology should as much as possible address the various issues of concern mentioned above. In those areas with a high generation rate of fresh FS (e.g. slums and emergencies), the reduction of pathogenic organisms should definitely be prioritized over sludge volume and organic matter reduction so as to minimize the risk of excreta-related disease outbreaks. The amount of the pathogenic organisms should be reduced to the recommended safe levels (e.g. *E. coli* to $\leq$1000 CFU/g TS and *Ascaris* eggs to $<$1 *Ascaris* egg/g TS (WHO, 2006)). Next to pathogen reduction, it is often desirable to reduce the FS volume (to minimize handling costs) and organic matter content (to avoid odour and disease vector nuisance).

A microwave (MW) based technology can be a viable option for the treatment of fresh FS from intensively used toilet facilities as it has been shown being regarding the efficient pathogen inactivation and volume reduction (Mawioo et al., 2016). MW irradiation uses the MW energy (E_{MW}) with wavelengths between 1 mm and 1 m and frequencies between 300 MHz and 300 GHz in the electromagnetic spectrum (Haque, 1999; Remya and Lin, 2011; Tang et al., 2010). The MW technology has been used in various applications, most of which involve the use of heat generation. In such applications, the heat is generated by the molecular motion in the target material resulting from the migration of ionic species and/or rotation of the dipolar species when they interact with the microwaves (Haque, 1999; Mawioo et al., 2016; Thostenson and Chou, 1999). Various benefits are associated with heating by MW (Haque, 1999; Mawioo et al., 2016). The heating of a material by microwaves depends on its dielectric properties (i.e. the dielectric loss factor and the dielectric constant) and materials with high dielectric loss factor are favorable for the MW heating. Various types of sludge, such as sewage sludge and blackwater sludge (i.e. sludge extracted from a blackwater stream generated in low flush toilets, TS = 12%) contain dipolar molecules (e.g. water and organic complexes) with high loss dielectric properties and have demonstrated a good response to the MW treatment (Mawioo et al., 2016; Yu et al., 2010). For instance, nearly complete bacterial removal was reported when sewage sludge (Hong et al., 2004, 2006) and blackwater sludge (Mawioo et al., 2016) were heated by MW to temperatures above 65 °C. Furthermore, over 70% sludge volume reduction was achieved by treating blackwater sludge (Mawioo et al., 2016) and anaerobic sewage sludge (Menéndez et al., 2002) with MW. The MW effect on the pathogen destruction is linked to both the non-thermal (electromagnetic radiation) and thermal (temperature) effects of electromagnetic energy (Banik et al., 2003; Hong et al., 2004; Mawioo et al., 2016). By electromagnetic radiation, molecules of the irradiated material orient themselves in the direction of the electric field, which may break the hydrogen bonds leading to the denaturation and death of microbial cells (Banik et al., 2003; Tyagi and Lo, 2013). Conversely, the destruction by thermal effect is caused by the rapturing of microbial cells when water is rapidly heated to the boiling point by rotating dipole molecules under an oscillating electromagnetic field (Hong et al., 2004; Tang et al., 2010; Tyagi and Lo, 2013). On the other hand, volume reduction is strongly linked to the temperature increase, which causes evaporation of the water contained in the sludge (Mawioo et al., 2016). Stabilization of organic matter in sludge was not achieved by MW heating, arguably due to the relatively low maximum temperature (i.e. 127 °C) attained in the treatment process (Mawioo et al., 2016). However, organic stabilization was achieved by Menéndez et al. (2002) when they mixed sludge with a MW receptor material to attain high temperatures (over 900 °C).

As discussed above, waste management by MW technology has been demonstrated through treating the various kinds of sludge. The technology possesses a rapid heating and treatment capability, which can be explored further for possible applications in treating fresh FS in slum and emergency settlements. Despite the reported successes in the various kinds of waste treatment, the information on the evaluation of the MW technology in FS treatment for a potential field application is still limited. So far, only a recent study evaluating the MW treatment of blackwater sludge has been reported; in which *E. coli*, sludge volume, and organic matter reduction was assessed (Mawioo et al., 2016). It is therefore highly needed to evaluate the potential application of this technology for specific field applications using fresh FS obtained from toilet facilities under real field conditions. In addition, the previous studies demonstrated pathogen reduction on *E. coli* and faecal coliforms; therefore, including other pathogenic organisms such as helminth eggs is also important, as they are shown to be more resistant to treatment (Feachem et al., 1983; Koné et al., 2007; WHO, 2006). If successful, the information derived from such study can help to further validate the MW application for treatment of FS under those conditions and set the basis for scaling up the technology. Also, the study can expand knowledge about the response of different types of sludge to MW treatment.

In this study the potential of a MW based technology for slum or emergency sanitation applications was evaluated by treating fresh FS obtained from toilets in the slums of Mukuru and Mathare in Nairobi, Kenya. Besides being a representation of FS in an urban slum environment, the fresh FS sample obtained in these conditions is also relatively similar to that which is generated in emergency camps. Three aspects of the proposed MW treatment technology were assessed in this research including the reduction of pathogens, sludge volume, and organic matter. Both *E. coli* and helminth (*Ascaris lumbricoides*) eggs were used as indicators for pathogen reduction, while the sludge weight was used to estimate the volume reduction. The organic stabilization of the FS was estimated using the volatile and total solids ratio (VS/TS) as indicator.

2. Materials and methods

2.1. Research design

This study was performed using fresh FS samples obtained from Fresh Life® toilets, which are installed and maintained by Sanergy in collaboration with entrepreneurs in the slums of Nairobi, Kenya. Fresh Life® is the brand name of Sanergy toilets that uses the principle of urine-diverting dry toilet (i.e. faeces and urine streams are diverted and collected in separate containers). The toilets are emptied on a daily basis by removing and replacing the filled