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Eco-efficiency analysis of sludge treatment scenarios in urban cities: the case of Hong Kong

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ABSTRACT

Urbanization is unrelenting due to rapid world population growth, necessitating a sustainable assessment with consideration of environmental impact to minimize resources inputs and waste outputs. An eco-efficiency analysis (EEA) framework has been developed to evaluate urban sludge handling options. Assessment of economic cost and environmental impact has revealed the suitability of the framework in urban application, as demonstrated by a case-study assessment of five sewage sludge management scenarios in Hong Kong. Land cost considerations, which are trivial in rural areas, have been revealed to be crucial in urban cities by the recognition of consequential sensitivity to high urban land costs. Furthermore, separate and detailed assessment of sludge treatment facilities based on actual transportation data are also highly significant because the accumulated GHG emissions associated with transportation can vary up to 187,000 tons when using single transportation distance assumptions. By the inclusive evaluation of sludge scenarios instead of individual treatment technology, comprehensive and informative results were obtained for sustainable town planning and sludge management. The EEA framework for urban sludge management developed in this study, which considers the economic and environmental aspects of the scenarios, enables informed sustainable town planning based on the priorities of the decision makers.

1. Introduction

Continuous global population growth and advancements in wastewater treatment systems have caused a significant increase in sewage sludge production worldwide. Municipal wastewater sludge contains pathogens, toxicants and heavy metals, thus poses potential hazards to human and the natural environment. Early in 1991, the recycling of sludge was encouraged by the European Union (EU) and sludge disposal to surface water was banned in 1998 (91/271/EEC, 1991). According to Fytili and Zabaniotou (2008), the sewage sludge production in the EU has been growing by 50% per year since 2005 due to the implementation of the Urban Waste Water Treatment Directive (UWWTD); and the sludge generation rates of EU members such as Italy and France in 2020 were predicted to be 1500 Mt, 1600 Mt of dry solids (DS) per annum respectively (European Commission, 2010). In the USA, sludge is generated at a rate of 6.2 dry Mt annually and continuous increase of the generation rate was expected (Kargbo, 2010). The proportion of sludge used for agricultural application is approximately 50% in both the EU and USA (European Commission, 2010; USEPA, 2015). In China, the current annual sludge production of over 20 Mt was expected to increase to more than 30 Mt due to urbanization and the escalating load of wastewater treatment plants (MOUHUR and NDARC, 2011). Processes adopted in China for sludge treatment include drying, thickening, dewatering, anaerobic digestion, incineration and composting; and the potential final destinations are agricultural application and landfill (Xu et al., 2014). Direct disposal of untreated sewage sludge has been reported in China, posing a high risk of soil, atmospheric and water pollution (Yang et al., 2012). With the recognition of the disastrous environmental and health risks, stringent sludge handling and disposal management is necessary.

Sludge is an unavoidable by-product of water and wastewater treatment processes. According to the information provided by the Hong Kong Drainage Services Department (DSD), Hong Kong will generate nearly 30,000 m^3 of sludge per day (EPD, 2008b) when the Harbour Area Treatment Scheme (HATS) Stage 2A is fully commissioned. All sewage sludge generated is mechanically dewatered in individual sewage treatment works (STWs) (ACE, 1999), and only sludge produced in the four major secondary

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STWs (Sha Tin, Tai Po, Shek Wu Hui and Yuen Long) undergoes anaerobic digestion (DSD, 2014). To explore the feasibility of sludge composting, sewage sludge is composted in a pilot study at the Ngau Tam Mei Animal Waste Composting Plant (EMSD, 2009). Landfills are the only destinations of sludge waste in Hong Kong. The current practice of co-disposal with construction wastes and municipal solid wastes (MSW) in the ratio of 1:10 is predicted to be unsustainable (EPD, 2008a); therefore a sludge treatment facility (STF) has been constructed. The STF, which is located in Tsang Tsui, Tuen Mun, uses fluidized-bed incineration technology for high-temperature combustion of sludge (EPD, 2005). To evaluate the appropriateness of various wastewater sludge treatment options adopted in Hong Kong, this study examines the performance of six treatment scenarios using eco-efficiency analysis (EEA).

The earliest concept of LCA emerged from energy analysis studies in the late 1960s and early 1970s. From 2002 to 2005, the Society of Environmental Toxicology and Chemistry (SETAC) published reports of their work on harmonizing the diverse frameworks and improving the LCA methodology. With the desire to codify the LCA methodology, standards for the LCA principle and requirements were specified in the International Organization for Standardization (ISO) 14000 series (ISO 14040, 2006; ISO 14044, 2006). ISO 14040 and 14044 provide a general framework without specifications for applications of LCA (Corominas et al., 2013). LCA studies have been conventionally conducted on products, but it is now gaining popularity as a tool for investigating the sustainability of different systems (Guinee et al., 2011), such as waste management and water management, by striking a balance between economic growth and environmental conservation (Chang et al., 2014). Early in 2000, a life-cycle approach for evaluating the sustainability of sludge reuse options was suggested (Bridle and Skrypski-Mantele, 2000). To provide comprehensive information and guidance for decision-making, LCA has rapidly developed as a sludge management tool for evaluating the lifetime performance of sludge treatment processes. Previous studies have been conducted at divergent scopes and scales under the flexible framework of LCA (Yoshida et al., 2013). Foley et al. (2010) carried out a study to reveal the life-cycle inventories of wastewater treatment scenarios without assessing the environmental trade-offs, using life-cycle impact assessment (LCIA). Conventional LCA that only focused on environmental consequences was conducted to analyze the resource consumption and environmental emissions associated with sludge handling processes (Suh and Rousseaux, 2002; Houillon and Jolliet, 2005).

To provide a more practical and comprehensive urban sludge management solution, the economic cost of the treatment scenarios was included in the EEA using the life-cycle cost (LCC) approach. To conduct an EEA, the environmental impacts are evaluated by the LCA methodology (Saling et al., 2002) and combined with economic analysis using life-cycle cost (LCC) approach (Kicherer et al., 2006). LCC methodology was adopted in addition to the traditional LCA in previous studies on sludge management (Hong et al., 2009; Lundin et al., 2004; Murray et al., 2008; Uggetti et al., 2011; Xu et al., 2014). To provide sound evidence for strategic sludge management decisions in urban cities, an EEA framework for urban sludge handling is developed for the evaluation of both the economic and environmental aspects with the inclusion of the characteristics of urban cities.

2. Goal and scope definition

2.1. Goal

The primary goal of this study is to develop an EEA framework that is suitable for sludge management in urban cities. Over the past years, LCA has been applied in a number of studies on wastewater treatment, but a mature framework designed specifically for compact urban cities has not yet been developed. For example, in the life-cycle impact assessment (LCIA) research conducted by Suh and Rousseaux (2002) and Houillon and Jolliet (2005), “land occupation”, which has a crucial impact in compact cities, was excluded. Hong et al. (2009) and Xu et al. (2014) included the impact of land use in their studies. However, the elimination of operating costs and capital costs of infrastructures led to inadequacies in their studies. Murray et al. (2008) and Xu et al. (2014) assumed that the transportation distances between the treatment facilities were 25 km and 40 km respectively. The assumptions led to inaccuracies in the estimation of atmospheric emissions associated with transportation. Hospido et al. (2010) conducted an environmental assessment on the agricultural application of reused sludge, which has a restricted significance for urban sludge management because of the limited agricultural activities in urban areas. Characteristics of urbanized areas such as limited land areas and high land costs were considered in the EEA framework for urban sludge management in this study, using Hong Kong as an example. The impacts of transportation were estimated based on actual transportation information.

Another goal of this research study is to assist decision makers in choosing the most appropriate sludge treatment approach for adoption in Hong Kong. To promote sustainability, wastes should be managed in an economically affordable, environmentally efficient and socially acceptable manner. LCA is a suitable tool to facilitate the development of sustainable waste management systems (Thomas and McDougall, 2005). The authorities in Gipuzkoa, Spain, chose LCA as an environmental tool for decision-making, and the findings of the LCA case study on waste management planning in Gipuzkoa demonstrated a success (Munoz et al., 2004). A research study conducted by Romero-Hernandez (2005) revealed the benefits that policy-makers can gain from implementing LCA on wastewater treatment processes and suggested the application of environmental tools to optimize treatment technologies using an evaluation of economic and environmental performance. Based on the actual conditions in Hong Kong, this study evaluated the economic and environmental consequences of six sludge treatment scenarios, with the aim of informing decision-making on sludge management in the city.

2.2. System boundary

A number of research studies have been conducted on the application of LCA to sewage sludge handling processes. A few of them have placed addition focus on specific treatment processes, such as the land application of anaerobically digested sludge (Hospido et al., 2010) and sludge treatment wetlands (Uggetti et al., 2011). Other studies compared the performance of various treatment technologies (Bridle and Skrypski-Mantele, 2000; Lundin et al., 2004). Sludge management scenarios that consisted of several treatment processes were set up in numerous studies. Murray et al. (2008) and Foley et al. (2010) analyzed the life-cycle inventories of the scenarios, while LCIA was included in the studies conducted by Suh and Rousseaux (2002), Houillon and Jolliet (2005), Hong et al. (2009) and Xu et al. (2014). In this study, sludge handling scenarios, rather than individual technologies, were investigated to offer more comprehensive results. The six scenarios, which were defined based on actual practices and conditions, involved different combinations of treatment processes used in Hong Kong (Fig. 1). As dewatering is a necessary process to treat sewage sludge, it was included in all scenarios and the method adopted is mechanical dewatering. In scenarios S1, S3 and S5, raw sludge is treated by AD prior to dewatering (Supporting