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Life-cycle environmental and economic assessment of sewage sludge treatment in China

Changqing Xu, Wei Chen, Jinglan Hong*

Shandong Provincial Key Laboratory of Water Pollution Control and Resource Reuse, School of Environmental Science and Engineering, Shandong University, Shanda South Road 27, Jinan 250100, PR China

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ABSTRACT

A cost-combined life-cycle assessment was conducted to estimate the environmental and economic burdens of 13 sewage sludge-treatment scenarios in China. Results showed that anaerobic digestion was a suitable alternative to reduce both environmental and economic burdens because this approach reduced dry mass volume and applied energy recovery. Landfill and incineration technologies had the highest and lowest environmental burdens, respectively. Direct heavy metal emissions generated from landfill and incineration processes contributed significantly to human toxicity and marine ecotoxicity. However, energy recovery from the landfill and incineration stages was important to reduce both environmental and economic burdens. This study indicated that a sewage sludge-treatment scenario with anaerobic digestion, dewatering, and incineration technologies was the most environmentally and economically suitable method to treat sewage sludge because of energy recovery. All new sewage treatment plants should be constructed to operate according to this method, and existing plants should be retrofitted.

1. Introduction

Significant amounts of sewage sludge are produced from sewage treatment plants worldwide. To date, the average annual outputs of sewage sludge in Germany, England, France, and America are 22, 12, 8.5, and 71 MT, respectively. In China, more than 20 MT of sewage sludge is generated annually (MOUHUR and NDARC, 2011). Aggravated environmental problems and increasing cost of sludge processing pose great challenges for wastewater treatment plants and policy makers.

Sludge contains large amounts of pathogenic organisms and heavy metals, which are harmful to human health and the environment (US EPA, 2007). Therefore, useful and effective methods are needed to remove pollutants, such as organic micro-pollutants and heavy metals. Approximately 71.5%, 40.6%, 10.8%, 38%, and 3.5% sewage sludge are treated in China by using thickening, dewatering, drying, anaerobic digestion, and composting, respectively (Ministry of Environmental Protection, 2010), with end-of-life treatment processes including landfill (31.03%), incineration (3.45%), and agriculture use (44.83%) (Wang et al., 2006).

Anaerobic digestion can regenerate electricity and heat by using the methane produced by sewage sludge. However, during the 11th Five-Year Plan in China, only 50 sewage treatment plants used anaerobic digestion. This number is less than 5% of all sewage treatment plants in China (Zhou, 2010). To provide useful information for policy makers on the rectification of sewage sludge-treatment plants, a comprehensive method for evaluating both environmental and economic burdens is highly needed.

Life-cycle assessment (LCA) is used to evaluate the environmental burdens associated with the whole life-cycle treatment of a product, process, or activity (ISO 14040, 2006). LCA has been widely used for eco-labeling programs, strategic planning, and marketing. LCA applications also include product design, process improvement, and consumer education.

LCA for sewage sludge-treatment has been widely studied worldwide. Yang et al. (1999) analyzed sludge treatment and disposal in China. However, they did not quantify the life-cycle inventory, and their results were ambiguous. Suh and Rousseaux (2002) evaluated five scenarios of sewage sludge treatment in France. These scenarios included incineration and landfill, lime stabilization and landfill, lime stabilization and land application, composting and land application, and anaerobic digestion and land application. Without considering energy recovery from landfill and incineration, they found that the anaerobic digestion and land application scenario was the most environmentally friendly

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* Corresponding author.
E-mail address: hongjing@sdu.edu.cn (J. Hong).

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method to treat sludge. Lundin et al. (2004) assessed the environmental and economic consequences of four options for sewage sludge in Sweden. These consequences include agricultural application, co-incineration with waste, incineration with phosphorus recovery, and fractionation. The conclusion was that agricultural use is a cost-effective solution that is appropriate for local conditions. However, they did not consider the electricity recovery of incineration. Houilon and Jolliet (2005) compared six scenarios of sludge treatment in Switzerland. These scenarios included agricultural spreading, incineration, wet oxidation, landfill, pyrolysis, and cement production. The results showed that specific incineration in fluidized beds and agricultural spreading are the most attractive processes. Notably, this study only focused on energy conservation and on the effect of emissions on global warming without considering other environmental burdens. Mario et al. (2007) established an environmental LCA of sludge treatment and found electricity generation from incineration process proved to be an environmentally friendly option in Italy. Nevertheless, they only analyzed three scenarios: anaerobic digestion of sludge plus incineration, incineration of undigested sludge, and anaerobic digestion of sludge with composting. They also did not present quantified inventory data. Murray et al. (2008) evaluated the environmental and economic effects of sewage sludge treatment in Chengdu, China and reported that the superior sludge handling option is anaerobic digestion followed by the use of sludge as fertilizer. However, they only listed an inventory of economic costs. Benefits, key air emissions, energy consumption, and other inventory data (e.g., material consumption and heavy metal emissions) were not considered. Hong et al. (2009) conducted an integrated study of sewage sludge-treatment options in Japan by considering both environmental and economic effects and drew the conclusion that the environmentally optimal and economically affordable method of sludge treatment in Japan was thickening, digestion, dewatering, and melting. Similar with aforementioned research (Houilon and Jolliet, 2005), they considered very few categories: global warming, acidification, human toxicity, and land use. Almudena et al. (2010) studied the reuse of anaerobic digested sludge in agriculture in Spain and found that land application is an acceptable option to handle digested sludge. However, they only analyzed the environmental effects with four categories: eutrophication, global warming, human toxicity, and terrestrial toxicity. Nakakubo et al. (2012) compared two sewage sludge disposal technologies, namely, sludge and food treatment and sludge-food waste treatment. The results showed that food waste digested with sludge was superior to the conventional separate processing of sewage and food waste. Nevertheless, only greenhouse gas emissions and phosphorus recovery were studied. Wang et al. (2013) evaluated the assessment of environmental effects of sludge-treatment processes in Taiwan. The treatment processes included carbonization, direct landfill, co-incineration with municipal solid waste, and mono-incineration. They drew the conclusion that carbonization, followed by co-incineration and landfill was the most preferable sludge-handling option overall. However, the environmental effect generated from heavy metal emissions in landfill and incineration was excluded.

To our knowledge, most previous studies consider only limited aspects of the environmental effects of sludge treatment or assess only certain sludge-treatment processes. Few studies have concentrated on both the environmental and economic assessment of sludge disposal in China. Thus, research needs to address certain issues to present a more credible assessment. First, a Chinese database of sewage sludge treatment should be introduced, and effective decisions for waste management should be encouraged. Second, the environmental and economic performances of all sludge-treatment scenarios with and without anaerobic digestion in China have to be compared with those employed in other countries. Third, the efficiency of raw material, energy, and processes in sludge treatment in China must be improved. Finally, managers and policy makers should be provided with useful information to help them make decisions regarding the problem amendment in sewage treatment plants.

In this study, LCA and life-cycle costing (LCC) are integrated to address the aforementioned needs, evaluate the environmental and economic effects of sewage sludge-treatment scenarios, and identify the optimal handling scenario. After investigating nearly all sewage treatment plants in China (Wang et al., 2006), 13 main scenarios of sewage sludge treatment are compared in this study.

2. Scope definition

2.1. Functional unit

The functional unit is the base for the treatment comparison in the life-cycle inventory. The management of one tone of dry sludge (DS) is selected. All materials, emissions, cost, energy consumption, and recovery levels are referred to this functional unit.

2.2. System boundary

Thirteen scenarios for sewage sludge treatment are considered in this study. Except for the scenario of gravity thickening with landfill (GL), six scenarios are included: (a) gravity thickening, anaerobic digestion, dewatering, and landfill (GAD_WL); (b) gravity thickening, anaerobic digestion, dewatering, and incineration (GAD_WI); (c) gravity thickening, anaerobic digestion, dewatering, and agricultural use (GAD_WA); (d) gravity thickening, anaerobic digestion, and landfill (GAL); (e) gravity thickening, anaerobic digestion, and agricultural use (GAA); and (f) gravity thickening, anaerobic digestion, drying, and agricultural use (GAD_rA). The remaining six scenarios are similar to the six aforementioned scenarios but without anaerobic digestion. Fig. 1 shows the system boundaries of the GL scenario and the six scenarios with digestion process. The processes of raw materials and energy production, road transport, direct emissions, wastewater treatment, energy recovery from anaerobic digestion, incineration, and landfill stages are also included. The infrastructure is excluded because of the lack of detailed information on sewage sludge-treatment plants and their raw material production sites. Moreover, the infrastructure exhibited very low contribution to the overall potential environmental effect (Hong et al., 2009).

2.3. Methodology

The life-cycle environmental effect results are calculated at midpoint by using the ReCiPe (Goedkoop et al., 2009; De Schryver et al., 2009) method. This method is the most recent indicator that is available for LCA analysis. The ReCiPe method can also define 18 midpoint categories: climate change, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, ionizing radiation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, and fossil depletion. The IMPACT 2002+ (Jolliet et al., 2003) method is used as a comparison to supplement and verify the applicability of the results attained from the ReCiPe method.

The conventional costs of all scenarios are assessed by using the LCC method, which is based on LCA but considers the costs rather than the environmental effects (Hong et al., 2009, 2012; Castella