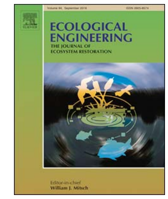
Ecological Engineering 110 (2018) 8–17

Contents lists available at ScienceDirect

Ecological Engineering

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



Research Paper

An emergy evaluation of the sewage sludge treatment system with earthworm compositing technology in Chengdu, China

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ARTICLE INFO

Keywords:
Sludge treatment/disposal
Emergy analysis
Emergy indicator
Sustainability

ABSTRACT

With the continuous social and economic development, the output of municipal sewage sludge is increasingly rising. Sludge treatment and disposal technologies need economical investment and resource consumption, and their comprehensive performance should be investigated from pros and cons, to provide systematic information for policy-makers. Based on the characteristics of sludge treatment and/or disposal systems, this study proposed an improved emergy approach which considered emissions' impact, and then it presented a set of indicator system to explore the comprehensive performance of sewage treatment/disposal practice. Application of the proposed method and indictors to one sewage sludge treatment system with earthworm compositing technology located in Chengdu, China results show that (1) the dewatered sludge is the main contributor to this system, followed by mushroom dregs; (2) direct emissions from diesel use should be emphasized; (3) this system can promote resource conservation effectively through lower emergy investment; (4) emissions' impact slightly reduces the comprehensive performance; (5) this system is not sustainable in the long term due to great dependence on nonrenewable resources. Finally, this work puts forward some improvement suggestions for the sewage sludge treatment practice.

1. Introduction

With the fast development of Chinese economy, the industrial and domestic water use has climbed by 23.84% from 1.71*10ˆ11 m^3 in 2000 to 2.12*10ˆ11 m^3 in 2014, while the related wastewater discharge has reached 7.16*10ˆ10 m^3 in 2014, which includes 2.29*10ˆ7 tons of COD (chemical oxygen demand), 2.39*10ˆ6 tons of NH_3-N (ammoniacal nitrogen), and 5.35*10ˆ5 tons of T-P (total phosphorus) (National Bureau of Statistics of the PRC, 2016). To protecting the local water body, the number of wastewater treatment plants had reached 4436 in 2014, with a total design capacity of 1.71*10ˆ8 m^3 and had an average daily treatment ability of 1.35*10ˆ8 m^3 (Ministry of Environmental Protection of the PRC, 2015). Meanwhile, the total sludge production in China had an average annual growth rate of 13% from 2007 to 2013; therein, 6.25 million tons of dry solids were produced in 2013. Sludge is a byproduct of the sewage treatment process, having characteristics of a high moisture content, high organic matter content, easy degradation and malodorous emissions, finely grained suspended solids, and a colloidal liquid (Liu et al., 2015). Sludge disposal is an expensive operation, which can also cause significant environmental pollution if dealt with improperly (Feng et al., 2015; Yang et al., 2015; Liu et al., 2014a; Zeng et al., 2012, 2014). Consequently, the sludge outlet has become one of the major bottlenecks for the sustainable development of wastewater treatment industry, and the limited investment and weak supervision further make this issue intractable (Yang et al., 2015).

The debate on different waste management practices has become a very important issue as human activities have overloaded the assimilative capacity of the biosphere (Marchettini et al., 2007). Italian law on solid waste management recommends an increase in material recycling and energy recovery, and only foresees landfill disposal for inert materials and residues from recovery and recycling (Marchettini et al., 2007). A reasonable waste management policy should be based on the principles of sustainable development, according to which our waste is not simply regarded as something to eliminate but rather as a potential resource. This requires the creation of an integrated waste management

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http://dx.doi.org/10.1016/j.ecoleng.2017.10.007
Received 20 March 2017; Received in revised form 30 September 2017; Accepted 8 October 2017

plan that makes full use of all available technologies.

Different methods have been used to evaluate the performance of sludge treatment and disposal from diverse angles, mainly including LCA (life cycle assessment) (Ramachandran et al., 2017; Gourdet et al., 2017; Abuşoğlu et al., 2017; Edwards et al., 2017; Pradel et al., 2016; Sebastião et al., 2016; Deviatkin et al., 2016; Buonocore et al., 2016; Mills et al., 2014), EE (economic evaluation) (Olkiewicz et al., 2016; Abus et al., 2016; Díaz et al., 2015; Cho et al., 2014; Venkatesh and Elmi, 2013), MFA (material flow analysis) (Vadenbo et al., 2014), and EFA (energy flow analysis) (Abus et al., 2016; Adar et al., 2016; Venkatesh and Elmi, 2013). LCA is a tool for assessing the potential environmental impacts associated with all the processes of a product's lifecycle (ISO 14040, 2006; ILCD, 2012); however, it ignores the quality differences between diverse material flows, and the analytic-hierarchy-process it adopts also incurs some subjectivity. The EE, based on the relationship between supply and demand and human willingness to pay, emphasizes money instead of the harmony between economic benefit and environmental cost (Yuan et al., 2011). The MFA, based on the law of indestructibility of matter, traces the material flows under a certain space-time condition, and gives resource efficiency in an easily understandable manner; however, it does not consider the quality differences between all sorts of materials, which is problematic for evaluating emissions' impact. EFA investigates the distribution of energy under a certain space-time condition, and shows energy efficiency of processes; however, it confuses the quality differences between different energy sources, derived from various natural processes and human activities. Therefore, these methods cannot provide a holistic picture when investigating a process. Especially they all overlook the contribution of natural capital to economic activities. And this is not helpful for policy-making on resource conservation and environmental protection even though we orally attach great importance to them.

Compared to the aforementioned methods, emergy analysis (EA), derived from systems ecology and energy ecology (Odum, 1996), can well overcome the flaws of these methods. Emergy is the sum of certain energy that is used to produce a product or provide some service directly and indirectly. It is a kind of energy memory or embodied energy, which traces the energy flow process from low quality energy to high quality energy. EA has been widely applied to waste management strategies, such as comparing three wastewater treatment systems (a constructed wetland, a cyclic activated sludge system, and a conventional activate sludge process) (Zhou et al., 2007), assessing the whole strategy of waste management (Marchettini et al., 2007), investigating performance of Macao's waste treatment (Lei and Wang, 2008), exploring feasibility of municipal wastewater treatment using constructed treatment wetlands (Arias and Brown, 2009), analyzing different recycling options for construction and demolition waste (Yuan et al., 2011), investigating the net emergy yield of the recovered materials of the Sorting and Composting Waste Treatment Plant in Sao Paulo, Italy (Agostinho et al., 2013), evaluating the sustainability of the cassava vinasse treatment (Yang and Li, 2013), investigating the performances of end-of-life treatment of crystalline silicon photovoltaic panels (Corcelli et al., 2017), etc. Sometimes EA and other methods are jointed to assess the comprehensive performance of a waste management system, such as EA and LCA (Gala et al., 2015), EA and EFA (Puca et al., 2017), Combination of MFA, EFA, EA, Emissions accounting and impact categories (Nikodinoska et al., 2017), etc. However, the study results of these applications are not complete as emissions' impacts have not been considered; meanwhile, jointed use of EA and other methods could lead to inconsistent conclusions due to different measure units and analysis boundaries. In recent years, some researchers have begun to consider emissions' impact in their emergy-related studies, including evaluating a municipal sewage treatment ecosystem (Zhang et al., 2010), assessing an integrated livestock wastewater treatment system (Zhang et al., 2014), comparing several scenarios for sewage sludge reduction and reuse in clinker production (Liu et al., 2015), investigating the sustainability of waste treatment systems (Winfrey and Tilley, 2016), etc. These studies have quantified emissions' impact in terms of emergy from different angles, and further strengthened the integration and systematicness of EA. However, some issues still need to be clarified, such as how to classify emissions' impact, how to correctly integrate different impact categories into the corresponding performance indicators, etc. This study contributes to the existing emergy indicators through distinguishing emissions' impacts into ecological service and emergy loss, and then integrating ecological service and emergy loss into environmental loading rate and emergy yield rate respectively. In doing so can one quantify pollution emissions' effect on the performances of different production systems more clearly.

Common sludge treatment and disposal technologies include landfilling, composting and agricultural use, and incineration. Therein, sludge composting is one promising sludge treatment technology. However, it still has some flaws, such as emissions of odorous gases, low added value products, etc. Improved sludge composting with earthworm breeding can overcome these shortcomings to great degree. In this study, a sludge composting plant with earthworm breeding, located in Chengdu, Sichuan province, China was chosen as a case study. This study aims at evaluating the environmental sustainability of this sludge treatment system using a modified EA to provide pertinent suggestions for the policy-making. The modification includes (1) quantifying emissions' impacts in terms of emergy, (2) classifying emissions' impacts into ecological service and emergy loss, and (3) then integrating them into environmental loading ratio and emergy yield ratio, respectively.

2. Materials and methods

2.1. Introduction of the sludge treatment plant

The plant we analyzed is located in Wenjiang district, in the west of Chengdu, China. The Wenjiang district (103°41′–103°55′E, 30°36′–30°52′N) has a total area of 277 Km^2. According to the local statistics (Chengdu Bureau of Statistics Internet, 2015), the annual air temperature averaged 15.5 °C, the annual rainfall 1.038 m, the annual sunshine time 1196.5 h, the solar radiation 3.63*10^9 J m^{-2}, the annual evaporation capacity 0.9536 m, and the annual wind velocity 1.2 m/s in this city. Its permanent (registered) population was 0.4757 million, and GDP was 5.86*10^9 USD (U. S. dollar) in 2014 (using an average exchange rate of 6.22 Renminbi (RMB) per USD in 2014).

The plant adopts the earthworm compositing technology for sludge treatment (Fig. 1). It has a sludge treatment capacity of 5*10^4 t/yr, with coproduced sludge manure and earthworm. Firstly, about 120–150 tons of dewatered sludge is transported to this plant per day, and then the sludge is mixed with mushroom dregs following volume ratio of 1:1, i.e. 70.6–88.2 tons of mushroom dregs per day. Then, a kind of bacteria substrate, with loose structure and nutrient rich, is formed. Next, aerobic microbial agents (including thermophile bacteria and mesophilic bacteria) are inoculated to the mixture. And the roles of aerobic microbial agents included enhancing the temperature of the sludge compost during early period of fermentation, prolonging high temperature period for killing harmful pathogenic bacteria and roundworm eggs, accelerating dehydration of compost materials, and promoting the maturity of composting through shortening the fermentation cycle. And then the fermentation process starts. After two-stage fermentation, the mixture becomes relatively stable. Next, the mixture will be treated using two technologies: one is keeping bacteria degradation of mixture until decomposition for producing organic fertilizers; the other is introducing earthworm into composting. Compared to traditional composting technologies, earthworm composting has higher efficiency and more complete degradation of organic matters; meanwhile, this technology can also accumulate heavy metals. Therefore, the final compost has more abundant nutrition and lower risk due to removal of heavy metals (Table 1). At the end of earthworm composting, the earthworm cast is collected and then smashed. After its