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The development of a natural heating technology for constructed wetlands in cold climates

Lieyu Zhang [a,*], Lin Mu [b], Ying Xiong [a,*], Beidou Xi [a], Guowen Li [a], Caole Li [a]

[a] *Chinese Research Academy of Environmental Sciences, Beijing 100012, China*
[b] *BioHaven Environmental Solutions (Beijing) Co., Ltd, Beijing 100000, China*

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ABSTRACT

Composting of different ratios of pig manure to reed straw was studied to be a natural heating technology of constructed wetlands (CWs) in winter. Among the mixtures of pig manure and reed straws in different ratios, the pure pig manure was the most suitable compost material for the heating system of CWs in cold climates and its life expectancy was about 40 days. The one-year validation test in real-scale CWs with composting of pure pig manure as natural heating system in winter proved that the heating system of CW with pure pig manure as compost material can work effectively and enhance the pollutants removal rate in winter. The water temperatures inside the CW with heating system in winter (15.7–21.7 °C) were higher than that of CW without heating system (9.2–13.6 °C). The mean areal load reduction of TN and of NH_3-N in winter of CW with heating system was 1.008 g/m^2/d and 1.08 g/m^2/d, which was about 120% more than that of CW without heating system.

1. Introduction

Constructed wetlands (CWs) have been recognized as cost-effective alternatives or useful compliments to conventional wastewater treatment systems (Brix and Arias, 2005; Tsihrintzis and Gikas, 2010; Scholz and Lee, 2005; Vymazal, 2009). CWs are effective treatment systems for decreasing concentrations of the total suspended solids (TSSs), biological oxygen demand (BOD), nitrogen, bacteria (*Escherichia coli*, total coliforms) and metals (Kadlec and Knight, 1996; IWA, 2000; USEPA, 2000). However, previous researchers have suggested that low temperatures limit the performance of CWs, particularly in removing nitrogen and phosphorus during the winter (Kadlec and Reddy, 2001). Wang and Wang (2003) found that the removal rate of total nitrogen (TN) by CWs in winter was 27% lower than that in summer. Usually a temperature of 15 °C is reported as a limit of reduced bacteria action which resulted in significantly decreased nitrogen removal in CWs (Vymazal, 1999; Kuschk et al., 2003; Stefanakis et al., 2011) and nitrification rates dropped rapidly to zero as the temperature decreased to less than 6 °C (Kadlec and Reddy, 2001). Low temperatures will not only affect the pollutant removal in CWs but can also cause the packing layer to freeze, result in pipes breaking (Wallace et al., 2001), and cause ice blockage clogs (Smith et al., 2005) and many other adverse consequences.

To be effective in winter, heat preservation or heating measures for CWs must be taken, which should be designed as an integral part of a CW system. Mæhlum and Jenssen (2003) found that additional protection using mulch (snow, ice, straw, rock wool, polystyrene, etc.) as a cover and a specific design (larger and deeper bed) was effective in protecting the system from freezing. However, relying on snow and ice cover does not provide reliable insulation during cold periods because snow pack is limited, the ice would need to be maintained constantly, and it is difficult for mulch to provide good insulation. The worst problem in using mulch as insulation is that even small breaches in insulation can result in substantial heat losses in flowing water (Callahan, 2000). Solar energy or wind power heating techniques cannot be widely used in CWs due to their high costs. Vegetation and aeration can be used in cold regions to prevent clogging and freezing (Muñoz et al., 2006); however, it is difficult for vegetation to survive in low temperatures, and aeration will require high costs and large energy consumption. Overall, these techniques cannot provide reliable insulation or heating measures for CWs in winter.

In rural areas, the animal husbandry industry generates large quantities of wastes, which must be managed under appropriate treatment measures to avoid negative impacts on the environment, such as soil and water pollution, odors and gaseous

* Corresponding authors at: Chinese Research Academy of Environmental Sciences, 8 Dayangfang BeiYuan Road, Chaoyang District, Beijing 100012, China. Tel.: +86 010 51095613.
E-mail addresses: zhanglieyu@163.com (L. Zhang), xiongying9904202@163.com (Y. Xiong).

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emissions (Burton and Turner, 2003). Zhu (2006) claimed that livestock and poultry manure are sources of biomass energy, where the energy of 1 ton of livestock and poultry manure is equivalent to 0.375 tons of standard coal by dry mass. This large amount of energy is released by microorganisms as they degrade organic matter. Most of the energy generated through the aerobic biodegradation of organic matter during the compost process is lost in the form of heat (Evans et al., 1982). It is possible to maintain the anaerobic process at a temperature greater than 35 °C by properly combining composting with anaerobic fermentation, as claimed by Zhang and Dong (2001).

However, conventional composting investigations focus on identifying good-quality fertilizer and obtaining a rapid rate of organic matter degradation, not optimizing the amount of heat released. In this study, the composting of pig manure and reed straw as a method to heat CWs in winter was investigated with the objective of determining the best ratio of the two compost materials, i.e., which ratio can generate the most accumulated heat and have the longest heat production duration, to test the compost heating effect on a real-scale CW in winter.

2. Material and methods

2.1. Material characteristics

The selected method to heat CWs in water was composting organic materials to produce heat. The materials used for heat production were pig manure and reed straw. Fresh pig manure was obtained from Bei Jing Bei Lang Zhong Pig Farm. Reed straw was obtained from Anxin District, Baoding, Hebei Province, China; a crusher was used to crush the straw into 1-cm particles. The characteristics of the compost raw materials are shown in Table 1.

2.2. Experimental design

The experiment contained 10 different ratios of pig manure to reed straw (Table 2), which represented the entire ratio scale. The initial moisture content was maintained at approximately 60%.

Each compost experiment was conducted in a foam box that had dimensions of 37 cm in length, 25 cm in width, 34 cm in height and 2.5 cm in thickness. Each side of the box lid had two $2 \times 2\ cm^2$ openings, which allowed the aerobic condition to be maintained in the foam box. The lid was closed and only opened when the materials needed to be stirred or sampled.

The compost experiments lasted 68 days, and the piles were turned every 7 days. Triplicate samples were collected from the top to the bottom of the piles after 0, 3, 6, 11, 17, 24, 31, 41 and 68 days. The compost temperature changes, the evolution of the calorific value (CV) of the compost materials, and the transformation of the dissolved organic matter produced during the composition were studied.

2.3. Analytical methods

2.3.1. Temperature measurement

The compost temperature was represented by the mean temperature at the top, middle and bottom layer of the pile (Fig. 1). Nine temperature measurement points at the three layers in the vertical cross-section at the midpoint of the foam box width along with the length direction were selected (Fig. 1). The temperatures were measured with a Pen-type digital thermometer (SP-E-17, Ningbo Kaitai, China).

Table 1
The percentage of total carbon (TC), the percentage of total nitrogen (TN), the percentage of volatile solids (VS), the percentage of moisture content (MC) and CV of pig manure and reed straw.

Material	TC (%)	TN (%)	VS (%)	MC (%)	CV(kJ/g)
Pig manure	34.44	2.77	68.56	63.23	16,589.93
Reed straw	45.07	0.78	92.68	4.20	16,293.37

Table 2
Ratio of pig manure (dry mass) to breed straw (dry mass) (PM (%)/RS (%)), ratio of carbon to nitrogen (C/N), moisture content (MC (%)) and volatile solids (VS (%)) in 10 composting groups.

Group	PM (%)/RS (%)	C/N	MC (%)	VS (%)
I	100.00/0.00	12.43	63.23	68.56
II	76.74/23.26	16.00	58.71	73.17
III	58.44/41.56	20.00	57.86	75.28
IV	42.35/57.65	25.00	59.92	76.74
V	30.81/69.19	30.00	58.83	77.02
VI	22.14/77.86	35.00	59.33	79.42
VII	15.37/84.63	40.00	58.02	87.06
VIII	9.95/90.05	45.00	60.38	86.83
IX	5.52/94.48	50.00	61.76	89.07
X	0.00/100.00	57.78	60.98	92.68

2.3.2. Quantity of heat released by biodegradation of the organic matter

All the samples were dried and analyzed to determine their CV, which was determined by a bomb calorimeter (XRY-1A bomb calorimeter, Shanghai Changji, China).

The quantity of heat produced in composting can be calculated as $Q_{out} = Q_{in} - Q_{end} - Q_m$, where Q_{out} is the quantity of heat released by the biodegradation of organic matter, Q_{in} is the initial material energy, Q_{out} is the final material energy, and Q_m is the quantity of heat consumed by microbial activities, which was negligible (Lei et al., 2011).

2.3.3. Extraction of dissolved organic matter (DOM)

Five grams of the sample was mixed with 50 mL of distilled water (1:10 ratio) for 24 h in a horizontal shaker at room temperature. The suspension was then centrifuged at 10,000 rpm for 15 min and then filtered through a 0.45-μm membrane filter. The filtrate was stored at 4 °C for further analysis or treatments.

2.3.4. Fluorescence spectroscopy

A luminescence spectrometric method was used to determine the DOM evolution in the compost piles with a fluorescence spectrophotometer (F-7000 FL spectrophotometer, Hitachi, Japan).

EEM spectra of the compost samples were obtained by scanning emission spectra as a function of the excitation wavelength. Emission wavelengths from 260 to 550 nm in 5-nm steps and excitation wavelengths from 200 nm to 450 nm in 5-nm steps were examined. The wavelength scan speed was set at 1200 nm/min.

MATLAB7.0 software was used to remove Raman scattering and Rayleigh scattering. EEM data were processed with Origin 7.5 (OriginLab Corporation, USA).

2.3.5. FRI analysis

FRI method (Chen et al., 2003) was adopted for the EEM spectra analysis.

The EEM spectra of the DOM were divided into 5 consecutive regions, i.e., I, II, III, IV and V. The excitation/emission wavelength range of regions I, II, III, IV and V were 230–250/280–330 nm, 230–250/330–380 nm, 200–250/380–520 nm, 250–440/280–380 nm, and 250–440/380–520 nm, respectively. According to Chen et al. (2003), regions I and II are protein-like fluorescence regions and originate from protein-like materials and phenolic compounds, region IV is a soluble microbial by-product-like fluorescence region, whereas regions III and V are fulvic acid- and humic acid-