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Intermittent operating characteristics of an ecological soil system with two-stage water distribution for wastewater treatment

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HIGHLIGHTS

- Two-stage water distribution used to improve denitrification effect in ESS.
- TN removal rate increased by 23.09% with the optimum water distribution ratio (2: 1).
- The system also had well performance for COD, TP and NH_4^+-N removal.
- The denitrification mechanism was analyzed basing on the nitrogen form in effluent.

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ABSTRACT

Ecological soil systems (ESSs) are usually used to remove nitrogen from wastewater. Due to the poor denitrification performance of traditional ecological soil systems (ESSs), this study proposes a two-stage water distribution system to improve the nitrogen removal. The effects of different distribution ratios on the system treatment effect were studied in an intermittent operation mode. After determining the optimal distribution ratio and intermittent operation conditions, the dynamics of system inflow, outflow, and nitrogen removal were monitored. Theoretical analysis of the denitrification mechanism was carried out. The results showed that the optimum water distribution ratio was 2: 1, and a mean total nitrogen removal rate of 60.42% was achieved, which is 23.09% greater than that is typically achieved by the single-section ecological system. Under optimum distribution ratio conditions, the system also demonstrated effective removal of chemical oxygen demand (COD), total phosphorus (TP) and ammonia nitrogen (NH_4^+-N), allowing the effluent to satisfy China's urban sewage treatment plant level B emission standards.

1. Introduction

Ecological soil technology (also called soil infiltration technology) is a kind of artificially enhanced ecological wastewater treatment technology that utilizes the coupled functions of soil, plants and microorganisms to absorb and utilize nutrients in wastewater and promote the growth of plants at the soil surface (Van Cuyk et al., 2001; Vadas, 2006; Adhikari et al., 2014). The technology was first applied in Japan in the 1970s, and the quality of effluent water treated by this technology was found to be better than that effluent from secondary treatment (Arye et al., 2011; Mienis and Arye, 2018). Subsequently, some developed countries also vigorously promoted ecological soil technology (Murakami et al., 2008; Assouline, 2013). For example, about 36% of rural households and scattered-living family homes in the United States utilize this technology to treat domestic wastewater (Bedbabis et al., 2014; Nasri et al., 2014). In addition, some countries have applied this technology to the advanced treatment of municipal wastewater (Neurath et al., 2004; Bhandral et al., 2009). For instance, the effluent water from secondary treatment in Israel's wastewater

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Nomenclature

ESS	ecological soil system
TN	total nitrogen
NO_2^--N	nitrite
TP	total phosphorus
COD	chemical oxygen demand
NH_4^+-N	ammonia nitrogen
NO_3^--N	nitrate
ORP	oxidation-reduction potential

treatment plants was treated by ESS and then recharged into an underground aquifer for reusing during the dry season (Bumgarner and McCray, 2007; Nojd et al., 2009).

ESS has the advantages of high effluent quality, low investment, simple operation and management while avoiding the generation of peculiar smells, mosquitoes and flies (Cederkvist et al., 2013; Olson et al., 2013). It is especially suitable for the treatment of dispersed and non-toxic rural domestic sewage. Generally, high removal rates of organic matter and phosphorus from wastewater is obtained by adsorption, filtration and microbial processes, however, the nitrogen removal remains unsatisfactory (Cho et al., 2009; Rajeb et al., 2009; Tedoldi et al., 2016). In ESSs, nitrogen removal is mainly achieved by plant absorption, microbial nitrification-denitrification and NH_4^+-N volatilization (Davidsson et al., 1997; Cho et al., 2011). However, NH_4^+-N volatilization mainly occurs at pHs >8.0, so is negligible in neutral and weakly acidic soils. Microbial nitrification-denitrification is the main pathway for nitrogen removal in ESS (Choi et al., 2013). Numerous studies have shown that high NH_4^+-N removal can be obtained in such systems, indicating a satisfactory nitrification effect (Corradini et al., 2011). However, TN removal is low, suggesting inhibition of the denitrification effect. Therefore, improving the denitrification effect is crucial for TN removal in ESSs.

As a kind of anaerobic bacteria, heterotrophic denitrifying bacteria usually need adequate nitrate (NO_3^--N) and carbon sources in anaerobic conditions (Zhou et al., 2017; Jia et al., 2018). The denitrification effect will be inhibited when the redox potential reaches 400–600 mV (Gutiérrez Gnecchi et al., 2012; Yuan et al., 2013). In ESSs, the majority of organic matter in the influent wastewater is usually consumed by aerobic bacteria, resulting in insufficient carbon source for the denitrification process, which inhibits the denitrification effect (Geza et al., 2013). Therefore, this study aims to improve the redox environment of ESSs by using a soil-zeolite-carbonized rice hull mixed matrix. A two-stage mode for wastewater distribution is applied to provide carbon source for the denitrification process to enhance nitrogen removal by the system.

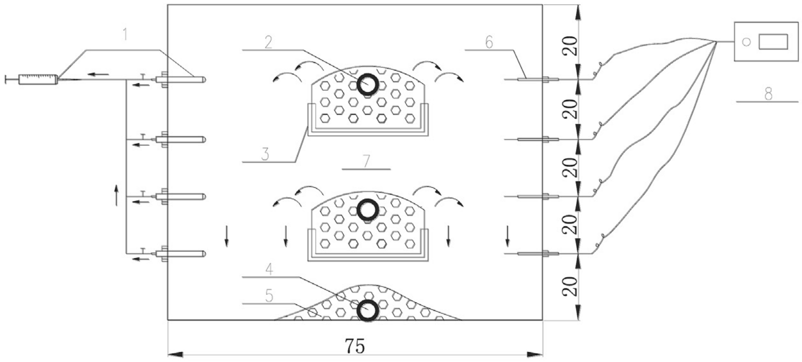
2. Materials and methods

2.1. Experimental reactor

As shown in Fig. 1, a lab-scale step feeding system (length × width × height = 75 × 60 × 100 cm) made of polyvinyl chloride (PVC) was set up for this study in a greenhouse at Shanghai Jiao Tong University (SJTU, Shanghai, China). The reactor was successively filled from bottom to top with 10 cm of gravel, 80 cm of mixed culture substrate (volumetric proportions of 80%, 5% and 15% of soil, zeolite and carbonized rice hull, respectively) and 5 cm of soil. The soil was collected from the meadow in the SJTU campus and sieved through a 5 mm mesh before installation. The wastewater was distributed through two perforated PVC pipes (named inlets #1 and #2) with inside diameters (IDs) of 32 mm placed at depths of 20 cm and 70 cm, respectively. The effluent was collected through a perforated outlet pipe (ID 25 mm) at the bottom.

2.2. Setup and operation

The experiment was conducted in two stages over 95 d. The system was initially operated for 30 d without step feeding in the start-up period, meaning that all wastewater was introduced into the system only through inlet #1 (Fig. 1). After operating for 30 d, a two-step feeding strategy was applied. During the step feeding stage, the influent volume was adjusted by a peristaltic pump and distributed to inlets #1 and #2, according to the step feeding scheme. Four schemes were examined including 3:1, 2:1, 1:1 and 1:2 for the water distribution ratio, respectively. The system was operated in step feeding mode for 65 d. In each period, the system was fed intermittently with synthetic wastewater, a flooding period of 24 h was followed by a drying period of 24 h. The mean influent flow rate was 18 L d^{-1} with a hydraulic loading rate of 0.04 m^3 m^{-2} d^{-1}. The synthetic wastewater was prepared with glucose (98%, Macklin, China) as carbon source, urea (99%, Aladdin, China) and ammonium chloride (99%, Macklin, China) as nitrogen sources in concentrations reflecting the domestic effluents in rural areas. The characteristics of the synthetic wastewater are shown in Table 1.



1. Sampling device; 2. Perforated distributing pipe; 3. Anaerobic tank; 4. Collecting pipe;

5. Gravel; 6. Electrode for ORP; 7. Matrix bed; 8. Potentiostat for ORP

Fig. 1. Schematic diagram of the step feeding subsurface infiltration system in the laboratory (unit: cm).