Development of natural treatment system consisting of black soil and Kentucky bluegrass for the post-treatment of anaerobically digested strong wastewater

Xiaochen Chen1,⁎, Kensuke Fukushi2

1. Department of Urban Engineering, The University of Tokyo, Tokyo 113-8656, Japan
2. Integrated Research System for Sustainability Science, The University of Tokyo, Tokyo 113-8654, Japan

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ABSTRACT

To develop a sound post-treatment process for anaerobically-digested strong wastewater, a novel natural treatment system comprising two units is put forward. The first unit, a trickling filter, provides for further reduction of biochemical oxygen demand and adjustable nitrification. The subsequent soil–plant unit aims at removing and recovering the nutrients nitrogen (N), phosphorus (P) and potassium (K). As a lab-scale feasibility study, a soil column test was conducted, in which black soil and valuable Kentucky bluegrass were integrated to treat artificial nutrient-enriched wastewater. After a long-term operation, the nitrification function was well established in the top layers, despite the need for an improved denitrification process prior to discharge. P and K were retained by the soil through distinct mechanisms. Since they either partially or totally remained in plant-available forms in the soil, indirect nutrient reuse could be achieved. As for Kentucky bluegrass, it displayed better growth status when receiving wastewater, with direct recovery of 8%, 6% and 14% of input N, P and K, respectively. Furthermore, the indispensable role of Kentucky bluegrass for better treatment performance was proved, as it enhanced the cell-specific nitrification potential of the soil nitrifying microorganisms inhabiting the rhizosphere. After further upgrade, the proposed system is expected to become a new solution for strong wastewater pollution.

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Introduction

In rural communities, strong organic wastewater is produced from many sources, such as livestock farming (i.e., animal excrement) and human excrement. This strong wastewater is usually of great concern, as without sound management it can lead to severe water pollution problems, such as eutrophication. Anaerobic digestion is generally considered the optimal treatment option, because it not only contributes to the decomposition of water-borne organic matters, but also generates biogas (methane) as a valuable energy source (Khanal, 2008). Nevertheless, the effluent of anaerobic digestion becomes another thorny problem. On the one hand, the organic pollutants could still exist in high concentration in this effluent (Park et al., 2010). On the other hand, the anaerobically-digested strong wastewater is typically characterized by a high content of nutrients, especially nitrogen (N), phosphorus (P) and potassium (K). Prior to discharge, post-treatment is still required, in order to avoid contamination of the receiving water bodies.

⁎ Corresponding author. E-mail: chenxiaochen1984@gmail.com (Xiaochen Chen).

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Land-treatment of wastewater has been practiced for a long period of time, and could be a feasible strategy for dealing with strong wastewater (Hunt and Poach, 2001; Yang et al., 2007). However, most of the conventional land-treatment technologies can barely provide satisfactory performance. Water-borne biodegradable organic matter represented by biochemical oxygen demand (BOD), once in high concentration, is fatal to the land-treatment process. First, the consequent rapid growth of heterotrophs can result in soil blockage and prevent water penetration (Rice, 1974). Second, oxygen is likely to be in deficiency, due to the consumption by the flourishing heterotrophic microbes. As a result, the nitrification process performed by soil nitrifying microorganisms could be seriously suppressed. As for the anaerobically-digested strong wastewater, in which NH$_3$-N constitutes the vast majority of all forms of N (Park et al., 2010), this nitrification inhibition implies a failed N removal process. In addition, normal plants can hardly survive growing conditions like nutrient-enriched wastewater (Munns, 2002; Yang et al., 2007). In that case, therefore, neither direct nutrient recovery through plant absorption nor economic benefit from biomass production can be achieved by the land-treatment process.

Aiming at developing a sound post-treatment process for anaerobically-digested strong wastewater, a novel natural treatment system is proposed (Fig. 1). The wastewater flows through the two units of this system in sequence. The first unit is a trickling filter, an aerobic fixed-biofilm process. Moderately high influent temperature is the key to the good performance of this unit, as it keeps the biofilm in a robust state throughout the two units of this system in sequence. The first unit is a trickling filter, an aerobic fixed-biofilm process. Moderately high influent temperature is the key to the good performance of this unit, as it keeps the biofilm in a robust state. The anaerobically-digested strong wastewater satisfies this requirement well, with a typical temperature of either 35°C (mesophilic) or 55°C (thermophilic) (Kim et al., 2002). Then a successful trickling filter unit benefits the following soil-plant unit from two aspects, i.e., (1) further removal of BOD, so that soil clogging and inhibited nitrification will not occur in the soil-plant unit; and (2) adjustable nitrification function, which controls the ratio of NH$_3$-N to (NO$_2^-$ + NO$_3^-$)-N in wastewater and may lead to their optimal ratio facilitating N removal and recovery in the soil-plant unit. Moreover, the plant is considered indispensable in this proposed system. For one thing, direct nutrient recovery and consequent market value from selling of plants are highly anticipated. For another, it is assumed that the growing plant can broadly enhance the soil microbial activity, especially the nitrification activity of soil nitrifiers, and hence bring about boosted nitrification efficiency. This ‘stimulation on nitrification’ hypothesis is based on our previous finding that alfalfa had a stimulating effect on the soil nitrifying microorganisms inhabiting not only the rhizosphere but also much deeper layers underground (Chen and Fukushi, 2014). As for the removal and recovery of P and K, retention by soil and absorption by plants could be the main routes.

A long-term lab-scale test was carried out as a feasibility study for use of this innovative natural treatment system as a post-treatment process for anaerobically-digested strong wastewater. With the main focus on its performance and mechanisms for the removal and recovery of major water-borne nutrients (i.e., N, P and K), the superiority of this system over conventional land-treatment systems was expected to be demonstrated. In addition, the ‘stimulation on nitrification’ hypothesis was tested to verify the essential role of the plant, and identify the scope and scale of its impact. Furthermore, suggestions for future upgrade and scale-up of this system were discussed.

1. Materials and methods

1.1. Soil and plant

The soil used in this study was commercially-available black soil, which is rich in organic matter content and arguably one of the best types of soils in terms of fertility, arability and supporting microbial activity. The basic properties of black soil (Table S1) were measured according to standard methods (Lu, 2000; Pansu and Gautheyrou, 2006).
Kentucky bluegrass (moonlight SLT) was selected as the test plant, which is a well-known turf grass for establishing sports fields. Compared to the field crops that are normally selected for building conventional land-treatment systems, Kentucky bluegrass has distinctive merits, such as better toughness and resistance under undesirable growing conditions (e.g., nutrient-enriched wastewater), higher nutrient removal capabilities, faster growth and higher biomass yield, higher economic value (around 3-4 US dollar/m² in the US market) and higher social acceptability (Tchobanoglous and Burton, 1991).

1.2. Composition of wastewaters

By comparison of compositions, it was discovered that pig manure and human feces had a similar ratio of total nitrogen (TN): total phosphorus (TP): total potassium (TK) (NATESC/MOA, 1999; Jönsson et al., 2005). Therefore, it was reasonable to select pig farm wastewater as representative of strong nutrient-enriched wastewater, higher nutrient composition of wastewaters (all values in mg/L).

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<th>Composition of wastewaters (all values in mg/L).</th>
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<td>Simulated wastewater</td>
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<td>Anaerobically-digested pig farm wastewater</td>
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BOD: biochemical oxygen demand; TN: total nitrogen; TP: total phosphorus; TK: total potassium.
During the whole test, the biomass of Kentucky bluegrass was harvested upon maturity from columns BTK and BWK, i.e., at approximately 4-week intervals. After oven-drying, the samples were weighed, and the cumulative weight from each column was recorded. At the end of week 67, the planting of Kentucky bluegrass was ended. Referring to standard methods (Lu, 2000), the harvested dry samples were digested to measure the concentrations of TN (=TKN + (NO2− + NO3−)-N), TP and TK, and then the total amount of water-borne nutrients recovered by Kentucky bluegrass could be calculated.

After 68 weeks of operation, it was confirmed that effluent quality reached stability, therefore the soil column test was terminated. Soil samples were immediately collected from different column depths, and analyzed for profile characterization of soil N (TN, NH3-N, (NO2− + NO3−)-N, organic N), P (TP and plant-available P) and K (TK and plant-available K), based on standard methods (Lu, 2000).

In order to verify the 'stimulation on nitrification' hypothesis regarding Kentucky bluegrass, as well as identify the scope and scale of its impact, soil samples were collected from different column depths immediately after the end of planting (i.e., end of week 67) and used for studies on the abundance and kinetic characteristics of soil nitrifying microorganisms. The abundance represented by cell numbers was determined by the most probable number (MPN) method, and the kinetic parameter reflected by nitrification potential (maximum nitrification activity) was obtained through a nitrification potential assay (Lu, 2000).

All statistical analysis (paired t-test) regarding comparison between treatments was carried out using the software SPSS Statistics 22 (IBM, USA).

### 2. Results and discussion

#### 2.1. Effluent quality monitoring

Effluent COD concentrations are presented in Fig. S2. With relatively low influent COD and BOD, soil clogging or water infiltration problems never occurred. The effluent COD concentrations were in general low, especially when the test approached the end. The cumulative COD removal efficiencies of columns BW and BWK were 92% and 95%, respectively.

With regard to N in the effluents, no organic forms were ever detected, and NH3-N had been successfully removed throughout the whole test. The result of effluent (NO2− + NO3−)-N is shown in Fig. S3. Compared to the influent TN composed of half NH3-N and half NO3-N, the effluent TN from columns BW and BWK consisted of almost 100% (NO2− + NO3−)-N. From week 26, the effluent (NO2− + NO3−)-N concentration of column BW started to rise, and reached 140 mg/L in the end. From week 36, an increasing trend was observed for column BWK as well, and the ultimate effluent (NO2− + NO3−)-N concentration was 187 mg/L. The higher concentration from column BWK could be explained by the higher evapotranspiration rate due to the presence of plants (24% for column BW versus 42% for column BWK). Apparently, the nitrification process operated very well in columns BW and BWK, while denitrification was unsatisfactory, which could also be indicated by the result of effluent pH (Fig. S4) (Tchobanoglous and Burton, 1991). The profiles of N in water throughout columns BW and BWK further elucidated the detailed treatment progress of water-borne NH3-N (see Fig. 2). With the infiltration of influent wastewater, the NH3-N concentration decreased rapidly, which manifested the great NH4+ adsorption capability of black soil. In addition, the (NO2− + NO3−)-N concentration in water rose dramatically to the maximum value within the top 10 cm, where the most active zone for nitrification must be located. Concerning the denitrification process, organic carbon functions as an indispensable electron donor. In this study, even without sufficient supplement from influent BOD, the stock of organic carbon in one black soil column was about 150 times more than the organic carbon required (calculated as glucose-C) to denitrify all the input N from wastewater for a period of one year. From this perspective, the bioavailability of organic carbon in the purchased black soil must be rather low, which could mainly exist in the form of inert humus. In terms of solving the denitrification deficiency, one feasible proposal for system improvement is put forward, i.e., concentrating on the functions of N adsorption (by plant and soil) and nitrification in the soil–plant unit, and utilizing a follow-up denitrification process to treat the effluents rich in (NO2− + NO3−)-N before...
discharge. In this case, the depth of soil could be cut to 20–30 cm, and consequently the cost for construction, operation and maintenance, as well as the risk of system failure, is expected to be greatly reduced.

TP in the effluents of columns BW and BWK was always at negligible concentrations. This excellent P removal performance could be primarily attributed to phosphate retention by black soil.

As depicted in Fig. S5, K removal was not successful. In competing with NH4+ for electrostatic attraction by black soil, K+ had handicaps such as poorer affinity (Pansu and Gautheyrou, 2006) and lower ion numbers in the applied wastewater, which were reckoned as the main cause of this phenomenon. Since K is not an environmental contaminant, this result raised no major concern.

2.2. Distribution of nutrients in the soil columns

Fig. 3 shows the distribution of various forms of N in the soil columns before and after the test. TN concentration decreased throughout the entire depth of all columns, except for the surface layer. This was due to the decrease of soil organic N, which was achieved during the degradation and conversion of soil organic matter. Moreover, columns BW and BWK receiving wastewater generally had higher soil TN concentrations than columns BT and BTK, which was attributed to the accumulation of inorganic N in soil, particularly the uptake of (NO2− + NO3−)-N. As for NH3-N, it mainly gathered in the top 20 cm of column BW. Its accumulation in column BWK was not confined to the surface layers, but also extended to a depth of 70 cm, probably due to the plant input such as root turnover. In general, the accumulation of NH3-N in soil was relatively trivial compared to that of (NO2− + NO3−)-N, and this phenomenon was considered a sign of sustainably excellent NH3-N removal performance for the proposed system. In contrast, if a land-treatment system dealing with ammonia-enriched wastewater does not have sound nitrification function, adsorption by soil becomes the primary mechanism of NH3-N removal. Sooner or later the system will produce effluents with increasing NH3-N concentrations, as well featured by the significant presence of NH3-N, rather than (NO2− + NO3−)-N, in the soil profile (Yang et al., 2007). Hence, there is a great risk of treatment failure.

The profiles of soil TP and plant-available P before and after the test are presented in Fig. S6. Input P was well secured in the top 10 cm of columns BW and BWK. The excellent retention of P by black soil involved many kinds of mechanisms, including precipitation and specific adsorption (Pansu and Gautheyrou, 2006). According to our previous study (Chen and Fukushi, 2013), P retention through specific adsorption also expanded the capacity of soil to adsorb ammonium electrostatically, which was one of the most important contributors to the excellent NH3-N removal performance. In addition, the concentration of plant-available P in the top layer far exceeded 20 mg/kg, the basic plant demand for available P in soil (Lu, 2000). Although not directly recovered by Kentucky bluegrass, this plant-available P in soil could be reused in an indirect manner, i.e., during sod harvest and system maintenance/renovation, the soil abundant in plant-available P could be removed and relocated to other fields with P insufficiency and support crop cultivation on them. According to the mass balance (Table S2) and plant-availability of P, the efficiencies of indirect P reuse from wastewater were 25% and 23% for columns BW and BWK, respectively.

After the test, the profiles of soil TK and plant-available K were in accordance with each other, which indicated that
nearly all the retained K remained plant-available (Fig. S7). Stored in soil mainly through electrostatic attraction, K could sustain its plant-availability for a long time. Similar to the case of P, indirect reuse of K from wastewater was able to be achieved. Taking into consideration K balance (Table S3) and its plant-availability, the efficiencies of indirect K reuse were calculated to be 62% for column BW and 69% for column BWK.

2.3. Harvest of Kentucky bluegrass

A higher concentration of nutrients existed in the Kentucky bluegrass receiving wastewater than that receiving tap water (see Table S4). Concentrations of TN, TP and TK in the harvested biomass from column BWK were 1.99, 6.10 and 1.56 times as high as those from column BTK, respectively. The total harvested weight from column BWK was 2.77 times that from column BTK as well. Mass balance calculation further demonstrated that the direct recovery of N, P and K from wastewater by Kentucky bluegrass took up 8%, 6% and 14%, respectively (see Table S5, Table S2 and Table S3).

2.4. Verification of the ‘stimulation on nitrification’ hypothesis regarding Kentucky bluegrass

Aiming at validating the ‘stimulation on nitrification’ hypothesis related to the impact of Kentucky bluegrass, the abundance and nitrification kinetic parameter of soil nitrifying microorganisms were determined and are illustrated in Fig. 4. Based on observation, the physical range of the rhizosphere of Kentucky bluegrass was the top 20 cm of black soil, although the majority of roots occupied the top 10 cm zone.

The results for living cell numbers reflected the fact that the abundance of soil nitrifiers was higher throughout the columns receiving wastewater than those receiving tap water ($R^2 < 0.01$). Except for the top 10 cm of columns BW and BWK where the average nitrifier cell numbers were close to $10^5$, in all depths of all the columns, the cell numbers were down by at least one order of magnitude. The results for the nitrification potential of soil nitrifiers displayed a similar pattern, i.e., higher nitrification activity was exhibited by nitrifiers inhabiting the top layers of columns BW and BWK ($R^2 < 0.01$). Especially at the very surface and 10 cm depth of column BWK, the nitrification potentials either approached or exceeded 28 mg N/kg-dry/day, the highest value in the summary by Norton and Stark (2011), which again confirmed the excellent nitrification function of the proposed system. It should also be noted that, in the top layers of soil, the nitrifiers of column BWK did not show a significant difference from those of column BW regarding cell numbers, nevertheless, they did show remarkably better nitrification activities ($R^2 < 0.01$). In other words, the positive impact of Kentucky bluegrass on the cell-specific nitrification activity of soil nitrifying microorganisms was clearly verified, together with the significance and necessity of Kentucky bluegrass to this proposed system. However, the confirmation of the ‘stimulation on nitrification’ hypothesis was confined to the rhizosphere of Kentucky bluegrass, because the abovementioned phenomenon disappeared beneath a depth of 20 cm. As oxygen scarcity underneath the top layers could have a significant inhibitory effect on nitrifier activities, the impact range of Kentucky bluegrass should not be hastily concluded as only encompassing the rhizosphere. In the future, moderately blending black soil with coarse sand and/or gravel before system construction could effectively improve its permeability for both water and air. Consequently, the system could bear a higher hydraulic loading rate of wastewater, and the scope and scale of the positive impact of Kentucky bluegrass on the nitrification function are expected to be expanded as well.

In terms of the explanation for the ‘stimulation on nitrification’ phenomenon, at least three mechanisms were likely to fuel the soil nitrifier activities in the presence of Kentucky bluegrass, i.e., the facilitation of downward transport of oxygen and water-borne substrate (NH$_3$) by plant roots (Tchobanoglous and Burton, 1991), the extra substrate (NH$_3$) input from plants (e.g., litterfall and root turnover) and the released plant rhizodeposition (e.g., exudates, secretions and sloughed off cells) (Paterson et al., 1997; Bertin et al., 2003).

For the sake of achieving the best treatment efficiency and land use efficiency, the proposed natural treatment system needs to be further tested under higher nutrient and consequent NH$_3$-N loading rates. In that case, the crucial role of Kentucky bluegrass in enhancing the nitrification function and guaranteeing the system sustainability should be thoroughly demonstrated. After this upgrade, this innovative natural treatment system is expected to be scaled up, and adopted by many rural communities as a sound approach for tackling the strong wastewater pollution problem.
3. Conclusions

The proposed natural treatment system consisting of black soil and Kentucky bluegrass fully displayed its feasibility as a post-treatment process for anaerobically-digested strong wastewater. It satisfactorily achieved the removal and recovery of major water-borne nutrients (i.e., N, P and K), and the long-term sustainability was identified as well through the detailed elucidation of the treatment mechanisms. Note that an improved denitrification process was still required before discharge. As one of the bright spots of this system, the outstanding nitrification performance in the face of ammonia-enriched wastewater was considered a big accomplishment, as the drawbacks of nitrifying microorganisms were well handled, including their low metabolic rate, demand for oxygen, susceptibility to inhibition by heterotrophs, and so on. Another highlight of this study was the discovery of the stimulating effect of Kentucky bluegrass on the nitrification activity of soil nitrifying microorganisms inhabiting the rhizosphere, based on which much better treatment efficiency and land use efficiency of the proposed system are highly anticipated. After further upgrade, this innovative natural treatment system is expected to be scaled up, and adopted by many rural communities as a sound approach for tackling the strong wastewater pollution problem.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jes.2015.05.030.

References


