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Comparative study of domestic wastewater treatment by mature vertical-flow constructed wetlands and artificial ponds

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ABSTRACT

This study compares the performance, design and operation variables of two wetland technologies treating domestic wastewater: an experimental artificial pond system and a mature experimental vertical-flow constructed wetland system. The wetland system planted with *Phragmites australis* (Cav.) Trin. ex Steud. (common reeds) was operated between June 2011 and October 2015, while the pond system was only operated between July 2015 and October 2015. Three different types of ponds were compared: ponds with wastewater; ponds with wastewater and reeds; and ponds with wastewater, reeds and aeration. Findings regarding the performances of mature wetlands showed that the wetland systems improved the water quality except for *ortho*-phosphate-phosphorus (PO_4-P), where the treatment performance reduced slightly over time. In general, the aerated pond systems showed better treatment performances in terms of ammonia-nitrogen (NH_4-N) and PO_4-P. Both systems were linked with medium to high levels of five-day biochemical oxygen demand (BOD) removal. The highest COD and SS removals were observed for wetlands in comparison to ponds. Moreover, mature wetlands were better in removing NH_4-N and PO_4-P than ponds unless the ponds were aerated. The nitrate-nitrogen (NO_3-N) concentration increased in the aerated ponds reflecting the high oxygen availability.

1. Introduction

1.1. Aim and objectives

This study aims to compare the performance of artificial ponds and mature vertical-flow constructed wetlands treating domestic wastewater using *P. australis*. The main objectives are to assess the mature wetland system effluent quality with time; the outflow water quality of different ponds and constructed vertical-flow wetlands; the performance of *P. australis* floating in ponds to abate COD, BOD, NH_4-N, NO_3-N, PO_4-P and SS from domestic wastewater; the impact of aeration in treatment ponds planted with *P. australis*; and the influence of operational parameters like contact time, resting time (system temporarily without influent) and loading rate on water quality.

1.2. Background

The pollutant removal from municipal wastewater is carried out using various technologies; however, biological treatment processes, which include assimilation, biodegradation, metabolism, adsorption, flocculation, precipitation and ion-exchange are often considered the most environmentally sustainable and cost-effective treatment options (Zanetti et al., 2012; Al-Isawi et al., 2016b), because they only depend on using common plants and microorganisms to remove pollutant loads from wastewater (Wu et al., 2012). Various types of wetland systems provide natural biological processes in addition to physical and chemical processes, and these combined developments are responsible for pollutant removal from wastewater (Nurk et al., 2005; Vymazal, 2011; Wu et al., 2014). Moreover, wetland plants have been successfully applied to treat domestic and industrial wastewater, and *Phragmites australis* (Cav.) Trin. ex Steud. (common reed) has been reported as an 'engine' for nutrient uptake from domestic wastewater, acting as a catalyst for purification by increasing the diversity in the rhizosphere, and enhancing a variety of biological and chemical reactions that support purification (Vymazal, 2007; Korboulewsky et al., 2012).

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Constructed wetlands are promising green treatment alternatives to conventional wastewater treatment units (Korkusuz et al., 2005; Wu et al., 2015). They have low investment and operational costs, yield high quality effluent with less energy dissipation, and are rather simple-to-operate (Scholz, 2010). Constructed wetland studies show that removal percentages of COD, SS and BOD are generally high, whereas removal points of nutrients (particularly nitrogen and phosphorus) are often lower and more inconstant (Vymazal, 2007; Paing et al., 2015). Among the various types of constructed treatment wetlands, vertical-flow constructed wetlands signify the state-of-the-art design attracting increasing interest worldwide (Stefanakis et al., 2014; Scholz, 2015). The main benefits of this design type are the lower area demands compared to that of other wetland systems (Scholz, 2010) and the fact that they provide sufficient oxygen within the bed for nitrification (Brix and Arias, 2005; Jia et al., 2010; Al-Isawi et al., 2015a; Murphy et al., 2016).

Recently, the application of constructed treatment wetlands and facultative ponds treating domestic sewage have attracted a lot of attention considering that they offer an environmentally sound method in the removal of nutrients and various pollutants (Chang et al., 2012; Pan et al., 2012; Ávila et al., 2013; Mburu et al., 2013). Most studies predominantly measured treatment performances of wetland systems, and little attention was paid to the age effect of sub-surface flow constructed wetland systems in terms of their treatment efficiency (Song et al., 2006; Dong et al., 2012). So far, there have been no substantial studies assessing the impact of mature constructed wetlands on the treatment performance based on efficiency comparisons with new treatment systems without fixed media such as artificial ponds. This paper fills gaps in knowledge and understanding by evaluating the capability of mature wetlands dissimilar in their designs and operations in producing effluent that is treated appropriately before release into the environment by comparing their efficiency with a new treatment system different types of artificial ponds. Three types of new artificial ponds were chosen in this study to assess the impact of mature wetland plants and the corresponding biofilm that developed around the gravel on nutrient removal and water quality.

Various researchers including Kadlec and Wallace (2009), Vymazal (2011), Scholz (2010) and Scholz (2015) have reviewed the effectiveness of constructed vertical-flow wetlands used for the treatment of urban wastewater. However, the impact of mature reeds (subjected to long-term studies) within constructed wetlands and passive aeration by operating them in tidal flow mode on the long-term treatment efficiency has been less well researched. Therefore, there is the research need to focus on the effect of reeds and aeration on the treatment performance of both mature wetlands and ponds. A comparison between the non-aerated ponds, the actively aerated ponds and the mature wetlands would allow for the assessment of the impact of passive aeration of wetlands systems on water quality parameters.

2. Materials and methods

2.1. Vertical-flow constructed wetland set-up

The vertical-flow constructed wetland set-up is located within a greenhouse (Fig. 1a; door left open) on top of the roof of the Newton Building, which is part of The University of Salford, Greater Manchester. The system comprises five filters and has been in operation since 27 June 2011.

The wetland filters were built from Pyrex tubes with inner diameters of 19.5 cm and heights of 120 cm. One filter was used as a control receiving clean de-chlorinated tap water. These filters were filled with siliceous ($\geq$30%) pea gravel up to a depth of 60 cm and planted with *P. australis*. The diameter of gravel used was 10 mm. Dead plant material was harvested from each wetland filter in the first week of January each year, cut into 2-cm long pieces and kept in an oven at 40 °C for 24 h. Directly thereafter, the dried cuttings were analysed and returned to the corresponding wetland filters by placing them on top of the litter zone (Al-Isawi et al., 2015b). The purpose was to simulate the natural decay of plants. This is in contrast to more managed systems, where cuttings would have been removed for good.

The wetland systems were constructed more than five years ago, and there was a lack of resources and space to construct replicates. This is a study limitation. However, many previous studies have been performed using similar wetland filters without replicates (Sani et al., 2013 ; Al-Isawi et al., 2015b; Al-Isawi et al., 2016a).

Table 1 demonstrates the statistical experimental set-up applied to test the impact of three variables: (1) contact time; (2) rest time; and (3) loading rate. Wetland 2 can be compared to Wetland 1 to assess the effect of a higher loading rate. The application of a lower contact rate is assessed through comparing Wetland 1 with Wetland 3. The impact of resting time was determined through a comparison between Wetlands 3 and 4.

Aqua Medic Titan chillers provided by Aquacadabra (Barnehurst Road, Bexleyheath, UK) were utilised to preserve the root system and debris layer of all experimental wetland systems at below-surface temperatures of about 12 °C to simulate natural conditions typical for the upper layer of the earth where the rhizome and root system of macrophytes would be located (Al-Isawi et al., 2015a).

2.2. Artificial pond set-ups

The pond system was located on top of a roof (Fig. 1b). The set-up includes four types of wetland filters. Table 1 shows an overview of the experimental set-up applied to test systematically the impact of three variables. Ponds 1–3 compared to Ponds 4–6 are used to test the impact of an elevated loading rate in terms of COD. The application of lower contact time is assessed between Ponds1 to 3 and Ponds 7–9. Finally, the impact of a lower resting time is assessed by comparing performance differences between Ponds 7–9 and Ponds 10–12.

In contrast to the operational parameters contact time, loading rate, and resting time, the authors defined the absence or presence of plants and active aeration as design parameters. Each pond set comprising three ponds is different in design. The first pond set contains only wastewater. The second pond set comprises both wastewater and *P. australis*. The last one contains wastewater, *P. australis* and is subjected to aeration. So, there are twelve ponds for four different treatment sets. In order to maintain experimental authenticity, another twelve ponds are used as corresponding replicates. During the start of the experiment, an equal quantity of *P. australis* (80 g of rhizomes i.e. wet weight); which contained around ninety nodes was introduces to the respective ponds.

Twenty-four cylindrical buckets (partly buried to avoid overheating; see also below) made-up of black plastic polymer with inner bottom and top diameters of 16 cm and 24 cm, respectively, as well as a height of 30 cm were used. The cylindrical buckets were placed inside large soil-filled concrete containers at 80% of their height, so as to simulate the natural conditions of ponds and to avoid contamination by the surrounding soil due to rain-splashing activity.

2.3. Operation method for vertical-flow constructed wetlands and pond systems

The comparative study has been carried out for three months (13 July to 13 October 2015) to assess the effluent water quality and removal efficiency of mature wetlands and immature ponds.