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Oxygen transfer and consumption in subsurface flow treatment wetlands

Jaime Nivala[a,b,*], Scott Wallace[c], Tom Headley[d], Kinfe Kassa[b,e], Hans Brix[a], Manfred van Afferden[b], Roland Müller[b]

[a] Department of Bioscience, Plant Biology, Aarhus University, Ole Worms Allé 1, Building 1135, 8000 Aarhus C, Denmark
[b] Helmholtz Center for Environmental Research (UFZ), Environmental and Biotechnology Center (UBZ), Permoserstrasse 15, 04318 Leipzig, Germany
[c] Naturally Wallace Consulting LLC, P.O. Box 2236, 109 E. Myrtle Street, Stillwater, MN 55082, USA
[d] Bauer Nimr LLC, P.O. Box 1186, Al Mina, Muscat, Oman
[e] TU Berlin, FG Siedlungswasserwirtschaft, Sekr. TIB 1B 16, Gustav-Meyer-Allee 25, 13355 Berlin, Germany

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ABSTRACT

Subsurface oxygen availability tends to be one of the main rate-limiting factors for removal of carbonaceous and nitrogenous compounds in subsurface flow (SSF) wetlands used for domestic wastewater treatment. This paper reviews the pertinent literature regarding oxygen transfer and consumption in subsurface flow treatment wetlands, and discusses the factors that influence oxygen availability.

We also provide first results from a pilot-scale research facility in Langenreichenbach, Germany (15 individual systems of various designs, both with and without plants). Based on the approach given in Kadlec and Wallace (2009), areal-based oxygen consumption rates for horizontal flow systems were estimated to be between 0.5 and 12.9 g/m^2-d; for vertical flow systems between 7.9 and 58.6 g/m^2-d; and for intensified systems between 10.9 and 87.5 g/m^2-d. In general, as the level of intensification increases, so does subsurface oxygen availability. The use of water or air pumps can result in systems with smaller area requirements (and better treatment performance), but it comes at the cost of increased electricity inputs. As the treatment wetland technology envelope expands, so must methods to compare oxygen consumption rates of traditional and intensified SSF treatment wetland designs.

1. Introduction

Subsurface-flow treatment wetlands are commonly used for the decentralized treatment of domestic wastewater prior to soil dispersal, irrigation reuse or surface water discharge (Kadlec and Wallace, 2009). Compared to conventional wastewater treatment technologies, treatment wetlands offer many advantages: they are low-cost, robust, simple to operate, and can be constructed out of locally available materials (Wallace and Knight, 2006). These factors lend to the widespread use and implementation of treatment wetlands in areas for which centralized sewage treatment is not a cost-effective option.

Aerobic conditions allow effective removal of many common wastewater constituents such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), and ammonium–nitrogen (Metcalf and Eddy Inc., 2003). In subsurface flow wetlands used for wastewater treatment, the oxygen demand exerted by the incoming wastewater generally exceeds the amount of oxygen available within the system (Kadlec and Wallace, 2009). As a result, oxygen transfer tends to be one of the main rate-limiting processes in subsurface-flow treatment wetlands.

Subsurface flow wetlands can be considered functionally similar to attached-growth bioreactors, with much of the pollutant degradation processes being undertaken by biofilms growing on the surface of the wetland substrate. Thus, for oxygen to be available for treatment processes, it can either be transferred to the water itself or to the biofilm surfaces. The prominent pathways of oxygen transfer in subsurface flow treatment wetlands are atmospheric diffusion, plant-mediated oxygen transfer, and convective flow of air within the pore space of the media (Brix and Schierup, 1990; Tanner and Kadlec, 2003; Kadlec and Wallace, 2009).

This paper reviews the mechanisms of oxygen transfer and consumption in treatment wetlands and provides an overview of the methods used to estimate oxygen transfer rates in these treatment systems. We also summarize the reported rates for commonly implemented treatment wetland designs. The findings from the review are then compared against new results from a pilot-scale facility in Germany that is comprised of 15 individual

* Corresponding author at: Helmholtz Center for Environmental Research (UFZ), Environmental and Biotechnology Center (UBZ), Permoserstrasse 15, 04318 Leipzig, Germany.
E-mail address: jaime.nivala@gmail.com (J. Nivala).

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wetland treatment systems. The main objective of the study was to investigate oxygen consumption rates of the various treatment wetland designs (horizontal flow, vertical flow, and intensified designs). The pilot-scale systems in Germany received the same primary-treated wastewater, enabling for the first time a true side-by-side comparison of various wetland designs. Planted and unplanted replicates were constructed in order to elucidate the role that wetland plants (*Phragmites australis*) play in oxygen transfer. Areal and volumetric oxygen consumption rates from the pilot-scale treatment systems are presented, and the limitations of current methods are discussed.

1.1. Atmospheric diffusion

Compared to free water surface (FWS) treatment wetlands, the actual surface area of the air-water interface in SSF wetlands is reduced by at least 60% due to the presence of the sand or gravel substrate. Mechanisms such as wave action and wind-induced mixing that contribute to surface reaeration in FWS wetlands are not operable in SSF wetlands; therefore atmospheric diffusion is the primary means of gas transfer. Atmospheric diffusion is further impeded by the fact that air generally must travel through a layer of unsaturated gravel and leaf litter before reaching the water surface. Because the rate of diffusion of oxygen is orders of magnitude slower through water than through air (Brix, 1993), passive diffusion processes are unlikely to have a significant impact on oxygen availability in conventional horizontal subsurface flow wetlands. Oxygen diffusion depends on various environmental factors such as water and air temperature, and degree of saturation of the bed. Tanner and Kadlec (2003) estimate that atmospheric diffusion of oxygen into a subsurface flow wetland system is on the order of 0.11 g/m^2-d, which for domestic wastewater treatment wetlands is an order of magnitude smaller than the oxygen demand of the incoming wastewater. While diffusion rates in conventional HSSF systems are quite low, diffusion can be significant in other types of treatment wetland designs, such as unsaturated vertical flow systems (Schwager and Boller, 1997).

1.2. Plant-mediated oxygen transfer

The role of plant-mediated oxygen transfer in treatment wetlands is one of the most highly debated topics in the literature. Internal transport of oxygen in wetland plants can occur via passive diffusion or through convective flow of air through plant aerenchyma (Brix et al., 1992; Brix, 1993). Oxygen release rates vary with plant species and season (Stein and Hook, 2005), as well as with the oxygen demand of the surrounding environment (Sorrell and Armstrong, 1994). In strongly reducing (e.g., wastewater) environments, wetland plants tend to minimize oxygen loss to the rhizosphere, which may limit the amount of oxygen released to growing root tips (Armstrong et al., 1990).

Some studies have aimed to directly measure plant-mediated oxygen transfer rates in SSF wetlands, while others have inferred oxygen transfer rates from water quality data. Reported rates of plant-mediated oxygen transfer in treatment wetlands span almost four orders of magnitude from 0.005 to 12 g/m^2-d (Table 1). Part of the variability in reported rates is due to differences in measurement techniques and the overall difficulty associated with measuring the oxygen concentrations at the root surface (Sorrell and Armstrong, 1994; Kadlec and Knight, 1996; Brix, 1997). There are also difficulties associated with extrapolating laboratory measurements to full-scale applications due to issues of scale and the non-homogeneity of root oxygen release (Brix, 1993).

Plant-mediated oxygen transfer in early Root Zone Method (RZM) systems was implied to be in the range of 5–25 g/m^2-d (Brix and Schierup, 1990). Similarly, a number of studies have measured oxygen consumption (based on an assumed stoichiometry for pollutant removal), and attributed that oxygen consumption entirely to plant-mediated oxygen transfer (Burgoon et al., 1989; Gersberg et al., 1989; McGechan et al., 2005). The general conclusion, however, is that the actual rates of plant-mediated oxygen transfer are not large enough to meet the demand exerted by primary treated domestic wastewater under common loading conditions (Brix and Schierup, 1990; Tanner and Kadlec, 2003; Bezbaruah and Zhang, 2005). As a result, many wetland design guidelines now neglect plant-mediated oxygen transfer altogether (U.S. EPA, 2000; Wallace and Knight, 2006; Kadlec and Wallace, 2009). Nevertheless, root release of oxygen and/or carbon compounds has been reported to affect microbial activity in SSF treatment wetlands (Zhu and Sikora, 1995; Gagnon et al., 2007; Faulwetter et al., 2009; Wu et al., 2011a). Such information suggests that while the rate of plant-mediated oxygen transfer may not be high enough to realistically meet the full oxygen demand of the wastewater, plants and/or root release of oxygen may indirectly affect treatment processes by changing the microbial community within the wetland bed (Dan et al., 2011).

1.3. Oxygen transfer at the water–biofilm interface

The limited oxygen transfer capability of conventional horizontal subsurface flow wetland designs has led to the development of alternative design configurations that improve the oxygen transfer to the subsurface zone (Brix and Schierup, 1990). These design configurations aim to provide sufficient oxygen for nitrification and removal of organic matter through use of shallow bed depth, intermittent dosing with vertical unsaturated flow, frequent water level fluctuation, or direct mechanical aeration of the gravel substratum. Although these "intensified" designs are gaining increased attention in the literature and in engineering practice, design standards for many of these types of wetlands have yet to be published (Kadlec and Wallace, 2009).

Early horizontal subsurface flow (HSSF) wetland designs were based on the Root Zone Method (RZM) (Kickuth, 1981). As discussed previously, plant-mediated oxygen transfer was thought to be a key mechanism in RZM designs, but actual oxygen transfer rates generally did not meet these design expectations (Brix, 1990) and the systems often clogged. This led to the development of vertical flow (VF) wetlands in the late 1980s (Brix and Schierup, 1990; Burka and Lawrence, 1990; Liénard et al., 1990), although the basic concept of these vertical flow wetlands goes back to the Max Planck Institute Process (MPIP) of Seidel (1966) and is similar to that of intermittent sand filters which have been in use for over 100 years (Crites and Tchobanoglous, 1998). These VF wetlands are intermittently pulse-loaded, and wastewater percolates through the unsaturated substrate. Ventilation pipes connecting a network of perforated drainage pipes to the atmosphere are often installed to provide a pathway for air to be drawn into the substrate from the bottom of the bed. Thus, air has an opportunity to enter the bed from either the top or the bottom and contact the biofilm between each loading event. This approach provides significant improvement of subsurface oxygen availability compared to HSSF designs. However, if VF wetlands are hydraulically or organically overloaded, ponding of wastewater occurs. This effectively cuts off air circulation and promotes clogging, which dramatically reduces oxygen transfer (Platzer and Mauch, 1997).

Based on hydraulic studies of typical HSSF wetlands, water was observed to bypass treatment by flowing under, as opposed to through, the plant root zone (Fisher, 1990; Breen and Chick, 1995; Rash and Liehr, 1999). García et al. (2005) investigated the treatment performance of side-by-side wetlands, some with a depth