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Nitrogen Removal and Sustainability of Vertical Flow Constructed Wetlands for Small Scale Wastewater Treatment: Recommendations for Improvement

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NITROGEN REMOVAL AND SUSTAINABILITY OF VERTICAL FLOW CONSTRUCTED WETLANDS FOR SMALL SCALE WASTEWATER TREATMENT: RECOMMENDATIONS FOR IMPROVEMENTS

by:

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1.0 Introduction

The goals of environmental sustainability, through minimizing resource use, maximizing energy efficiency, reducing waste emissions, enabling recycling, and increasing resilience are becoming primary in wastewater treatment, along with traditional goals of protecting human health and water quality. Sustainable designs, defined as design of human/industrial systems to ensure that use of natural resources and cycles do not lead to diminished quality of life due to losses in future economic opportunities or to adverse impacts on social conditions, human health, and the environment (Mihelcic et al., 2003) are needed to provide or replace sanitation policy and technology to meet increasing demands. The challenge for wastewater professionals is to design and operate treatment processes which are environmentally sensitive throughout the life-cycle and support human well being. This research focused on one technology for small-scale wastewater treatment: the vertical flow constructed wetland (VFCW), which was investigated for the capacity to remove ammonium and nitrate nitrogen from wastewater.

2.0 The Need for VFCW Research

Nature-based wastewater treatment systems that depend on the sun, air temperature, microbial life, soil or plants have potential sustainability benefits because of the low need for energy and chemical inputs (Crites and Tchobanoglous, 1998; Fuchs, 2009). A recent sustainability indicator study which evaluated wastewater treatment technologies suggested that land based treatment systems may provide more balanced social, economic, and environmental sustainability than mechanical systems when flows are less than 1 MGD (Muga and Mihelcic, 2008). Constructed wetlands are a nature-based system for treating domestic sewage, stormwater, industrial wastewater, and agricultural runoff (Kadlec and Knight, 1996). They can be a low-impact and sustainable technology which produces benefits above and beyond conventional wastewater treatment: green space, air filtering, wildlife habitat, biodiversity, decreased energy costs, nutrient recycling, reuse of effluent for agriculture or irrigation, and potential source of animal feed or biofuel crop. Constructed wetlands can provide a service vital for human survival and sanitation in an ecological system that may require less material and energy inputs than conventional treatment systems. Research on wetlands and other nature-based treatment systems is thus important in moving towards a sustainable future.

VFCWs have been used for wastewater treatment in Europe and the U.S. (Wallace and Knight, 2004). VFCWs have proven effective for secondary wastewater treatment and may be preferable over horizontal flow systems because they require much less land area. VFCWs typically employ a downward hydraulic regime, which researchers have shown is effective for removing ammonium from wastewater at the laboratory and field scales (Breen, 1990; Farahbakhshazad and Morrison, 1997, 2000; Moreno et al, 2002). In contrast, little research has been done on upflow wetlands, which may have the advantage of saturated, anaerobic conditions beneficial for denitrification (reviewed in Langergraber, 2008; Toscano et al., 2009). VFCW design has been based only on empirical observations and rules of thumb (Langergraber and Simunek, 2006; Gross et al., 2007; Cooper, 1999), making it impractical for optimizing system design and operation. A better understanding of the biochemical transformations occurring in the vertical flow regimes will give designers more practical information about the use, design and operation of constructed wetlands for wastewater treatment.

Gaseous nitrogen emissions have also become important. Nitrous oxide gas, which forms during nitrification or denitrification at non-optimal operating conditions, is a greenhouse gas with a global warming potential 20-30 times as great as carbon dioxide, and remains active in the atmosphere many times longer. NO_x (nitric oxide and nitrogen dioxide together) emissions form photochemical oxidants or "smog", which have known cancer risks. NO_x and other greenhouse gas emissions have been reported to be higher in vertical flow constructed wetlands than horizontal flow constructed wetlands (i.e., Sovik et al., 2006). Designers should consider that wetlands designed for nitrification-denitrification may also produce gaseous N emissions. Instead of reducing environmental problems, the problems might just be transferred from water to air and the tradeoffs should be considered.

3.0 Guidelines for VFCWs

Based on experimental and modeling results that this research investigated, several improvements in vertical flow wetland design for nitrogen removal can be recommended:

- Different VFCWs (downflow, upflow, or in-series) may apply depending on the nitrogen characteristics of the wastewater as well as the nitrogen species of concern. For wastewater high in ammonium and low in nitrate, where only nitrification is of interest, unsaturated downflow wetlands are the best choice. For nitrified wastewater where denitrification is needed, saturated upflow wetlands (with a carbon source) will provide the best results. A downflow and upflow wetland in-series may be the best option in cases where wastewater requires nitrification and denitrification.
- Because denitrification depends on available carbon, it may be best to take advantage of wastewater-carbon (readily biodegradable chemical oxygen demand (COD) early before it degrades, inferring a recycle of nitrified wastewater. The recycle could loop back to the influent tank or could be part of an upflow-downflow in-series arrangement (opposite the in-series columns in this study) with recycle of effluent back into the upflow wetland.
- A longer hydraulic retention time (HRT) for upflow wetlands should lead to more denitrification because of the slow hydrolysis of slowly biodegradable COD into readily biodegradable COD. For an upflow wetland, increasing the HRT means simply increasing the volume; however, increasing the depth is preferential to increasing the surface area, so that oxygen diffusion effects are not increased.
- A surface area of 1.1 m^2/p.e. was sufficient here for a nitrifying downflow column (where 1 p.e. = 150 L/d) according to the bench-scale experiment. Compared to current vertical flow constructed wetland guidelines of 3.2-5 m^2/p.e., the VFCW surface area could be significantly reduced. The recommended surface area is equivalent to a hydraulic load of 142 L/m^2d.
- This study showed that a small volume with high pumping frequency (48 pulses per day) produced the oxygenation necessary for full nitrification in the downflow wetland without flooding or clogging.
- Downflow wetland depth could be reduced by up to 70% from the 1 m guideline. Both the experimental and modeling results showed that nitrification occurred in the top 10-20 cm of the downflow column, and that further nitrification occurred in the top 20 cm below the water table in the upflow column. Depth reduction is not recommended in cold climate regions where the wetland may freeze.

- Upflow wetland depth could be increased by up to 0.6 m (from the 0.4 m saturated depth of the experiment; no design guidelines exist for upflow wetlands) to increase the hydraulic retention time to allow denitrifiers to consume slowly biodegradable COD and reduce the influence of oxygen diffusion.
- Vegetation should be included in denitrifying wetlands. The mechanism for nitrate removal with the presence of plants is not clear, but this study showed that vegetation has a clear positive influence (>10%) on nitrate and total nitrogen removal.
- Vegetation should have a low C/N ratio (<15), high potential photosynthesis rate, and large leaf area index (most fitting would be a productive but small-structured terrestrial species) in order for plant metabolism to play a role in nitrogen removal.
- The soil media used in this study was medium-grained sand, which is recommended for vertical flow wetlands along with the hydraulic load and pumping schedule in order to create the hydraulic conditions for advective oxygen transfer and avoid pore clogging.

Because the biochemical mechanisms depend on the arrangement of the whole system, the design recommendations listed above should be taken as an integrated concept For example, reducing the surface area of a downflow wetland but maintaining a flood-and-drain hydraulic loading regime will produce different oxygen transfer (and thus nitrification) results. Likewise, the unsaturated flow characteristics (which, along with the hydraulic loading schedule, determine advective oxygen transfer) of the downflow column are dependent on the specific soil media.

Recommendations should also be tested at the field scale. In particular, the unit surface area, reduced downflow depth, and small-volume/high-frequency pumping schedule should be tested with a variety of wastewater concentrations and throughout the year in regions where seasonal temperatures may be low. The reduced downflow depth may be more susceptible to freezing in winter temperatures. The unit surface area may not be appropriate if system influent concentrations are highly variable.

The design recommendations above are supported by the results of the life cycle assessment (LCA) which compared the life cycle environmental impacts of vertical and horizontal flow constructed wetlands. Optimizing nitrification and denitrification with the recommendations from this study will reduce the production of greenhouse gas emissions from the wetland wastewater treatment process. Improvements in the treatment process will reduce impacts due to respiratory inorganics, climate change and acidification/eutrophication by minimizing gaseous and aqueous emissions from the wetland. Reducing the depth of a downflow wetland will lead to a significant decrease in the material requirements of the wetland, reducing transportation and heavy machinery impacts; however, the addition of an upflow wetland for denitrification would neutralize the benefits of reduced volume. However, adding the denitrification capacity would reduce the eutrophication potential of the system. Using local or on-site materials rather than transporting sand and gravel from a distance would also reduce the fossil fuel impacts of the wetland life cycle. Finally, the LCA results show clearly that a VFCW is preferable to an HFCW for wastewater treatment for all impact and damage categories.

4.0 Research Conclusions

This research demonstrates significant conclusions for the wastewater treatment industry. First, VFCWs are an efficient and low-energy technology for wastewater nitrification, and have excellent potential for denitrification. They require significantly less land use than a horizontal flow constructed wetland (HFCW) and achieve water quality standards at much lower environmental impact than HFCWs and therefore much lower impact than conventional wastewater treatment (inferred from previously cited reports that HFCWs have lower impact compared to conventional technologies). The consideration of resource conservation and reduction of environmental impacts is becoming a priority in engineering design. Wastewater treatment technology and management needs to consider water, energy and nutrients as resources to recycle rather than wastes to separate. Constructed wetlands may be an appropriate solution for resource recovery and reducing environmental impacts.

Secondly, the design contribution of this work, though still in the form of "guidelines", is a much more holistic concept of vertical flow wetland function than the rule-of-thumb guidelines currently available (Danish and Austrian guidelines, previously cited). Because a constructed wetland is a complex ecosystem integrating soil, vegetation, microbes, and wastewater constituents, design equations (such as 1^{st}-order kinetics or advection-dispersion equations) cannot adequately describe the multiple processes and feedbacks. The ability to model the downflow and upflow processes with HYDRUS-2D/CW-2D demonstrates the understanding of many of the oxygen and nitrogen fate and transport mechanisms at work simultaneously. The design recommendations from this study are an improvement on available guidelines because of their basis in the mechanisms established from the experimental and modeling results.

5.0 Recommendations for Future Work

Questions remain regarding nitrogen removal in constructed wetlands and vertical flow wetland design:

1. Pilot- or field-scale observations would help to confirm the observations of this study and the verification of the model. Testing the recommendations from this work at the field scale would also would show whether the recommended design is feasible at low temperatures or with highly variable wastewater concentrations. With model parameters verified, the model could be used for studying design and operational configurations to optimize oxygen transfer and nitrogen fate.

2. Further bench-scale experiments or modeling could investigate the influence of other hydraulic loads or pumping schedules on oxygen transfer and nitrogen removal. They could also be used to test different wetland configurations such as the upflow-downflow-in-series or recycle as mentioned in the design recommendations.

3. Experiments are needed to gain further understanding of the impacts of COD fractionation and vegetation on denitrification and wetland design. Bench-scale experiments could also be conducted to determine greenhouse gas emissions from various wetland configurations, to determine design parameters which will maximize nitrification and denitrification but minimize greenhouse gas formation.

This research does not advocate that vertical flow constructed wetlands are always the optimum wastewater solution. Environmental resource cycles, including water, energy and nutrients, are becoming important as these resources diminish. Expanding the scope of environmental studies to include those resource cycles will offer keys to new solutions for wastewater treatment, which may include decentralization, ecological technologies such as vertical flow constructed wetlands, source separation of urine and feces, and will need to include energy and heat recovery, water reuse, and nutrient recovery. Management of sustainable wastewater systems will need to change as the technology and infrastructure changes, especially as decentralization occurs. Finally, sustainable solutions to wastewater treatment will require progressive policy actions so that technology and management systems will be adopted. An integrated research system that considers the resource cycles, policy and management systems, and technical development is needed to meet the challenge.

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