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Nutrient Removal by Root Zone Treatment Systems : A Review

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The Root Zone Treatment System (RZTS) has been used widely for nutrient removal in European countries. In spite of having its more adaptability in tropical region like India its use to address nutrient induced issues in the country is very less. The lack of widely accepted data, non consensus of scientists over nutrient removal mechanism and inability to apply performance standards observed in other countries directly might have hampered the acceptance of this technology in India. A few technology assessment programs are being conducted in collaboration with other countries to engineer this technology but nutrient removal aspects are not essentially focused. In this context, there is need to direct lab scale research to identify potential wetland plants, bed media and comparative study of their combination specific performance under similar conditions. The field application of the data will help to understand variability in performance and disparities in the mechanism. The systems would be amended based on these studies to establish combination specific performance standards for typical Indian conditions. Maintenance strategy and optimization of design will help to foster the technology. The development strategy should give due consideration to the contributions of other countries so as to avoid repetition of work which will save time, money and efforts, and help for the real acceptance of RZTS in Indian conditions.

Key words : *Root zone, nutrient, wastewater, pollution*

Introduction

In India, only 26% of the total generated wastewater receives treatment and a large part of the domestic sewage is not even collected[1]. Domestic sewage contains large quantity of nutrients in the form of Nitrogen (N) and Phosphorus (P) in addition to other harmful constituents. In most of the cases, untreated, treated or partially treated domestic sewage is generally disposed of into nearby water bodies or through land application. The high concentrations of nutrients in surface water degrade the habitats of fishes and other aquatic organisms. The increased levels also cause eutrophication and lead to rapid growth of algae in water bodies making them unsuitable. Nitrate causes blue baby syndrome, especially to infants. Chronic consumption of high level nitrate may also cause some cancers and teratogenic effects. It also reduces assimilation of iodine by human body causing goiter and may also lead to birth of malformed child[2]. There are various parts of India suggesting increased levels of nitrates in ground water.[3,4,5,6,7] The nutrient induced pollution is a serious problem in most of the cities of India. Advanced treatment systems, such as air stripping, reverse osmosis, ion exchange, electrodialysis etc., may address this issue but are not practically feasible and even affordable for small waste producers. Therefore, such appropriate wastewater technologies are required, which can be adopted, owned and operated easily at decentralized locations. In this context, constructed wetlands are potential decentralized treatment systems.

The Constructed Wetland Treatment Systems (CWTS) are typical engineered treatment systems designed and operated on natural principles involving wetland vegetation, supporting bed medium and their associated microbial assemblage for the treatment of variety of wastewater. The systems are usually classified as horizontal Surface Flow (SF), horizontal Subsurface Flow (SSF) and Vertical Flow (VF) based on wastewater flow configurations. CWTS have proved to be well suited for treating variety of wastewater in urban, suburban and rural areas of European countries[8]. On the contrary, only few CWTS are installed to study poetential applicability of this technology in India till date.

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removal over a period of five months. They found that phosphorus removal was superior in the soil-based systems with a mean P reduction from the influent concentration (24 mg/L) of 80% compared with 54% in the soil less bed. Recycling the effluent into the system in order to increase the detention time did not contribute to improving removal, except in the soil less bed. According to them, P removal in the soil-based systems is rapid, and an equilibrium value may reach beyond after which no further removal is possible. The effect of a lime amendment on the improvement of P removal was also studied in batch tests. The results suggest that P removal from wastewater can be greatly enhanced by the addition of small amounts of lime to the soil substrate.

Maschinski[26] carried out his studies on three RZTS cells in series using 16 previously untested native *Arizona* plants. The TKN removal found to be 73%. He observed that a combined nitrification/denitrification process is active in the system. After 9 months of operation, he found nitrification rates exceeding compared to denitrification rates and he also found that the wetland cells are aerobic.

Cottingham, *et al*[27] assessed the hypothesis that increasing available oxygen by aeration of the wastewater in the treatment beds increases nitrification and nitrogen removal rates. They used two pilot scale constructed wetlands (30m x 5m), one planted with *Phragmites australis* and the other serving as an unplanted control to treat primary domestic sewage. Prior to aeration, the influent nitrogen load in the wastewater passing through the beds was reduced by approximately 45% and 10% in the planted and control beds respectively. The aeration of the wastewater results in nitrogen removal of 51% and 20% for the planted and control beds respectively. High rates of nitrification were recorded for the planted bed with aeration, but removal of nitrogen by denitrification was limited, because of the absence of a suitable carbon source. High nitrification rates were not recorded in the unplanted control bed.

Del Bubba, *et al*[28] investigated nitrogen removal in a pilot-scale RZTS, planted with *Phragmites australis* and receiving domestic wastewaters for two years. They found that nitrification and denitrification simultaneously occurred in this system, showing the presence of both aerobic and anaerobic sites.

Drizo, *et al*[29] investigated ammonium distributions in a pilot-scale RZTS with *Phragmites australis* and shale as bed medium. The system was set up in a greenhouse, and comprised of four tanks with *Phragmites australis* and four tanks without *Phragmites australis*. In the planted systems, NH_4^+ - N concentrations were low at all depths throughout their length. Generally, NH_4^+ - N concentrations decreased exponentially along transect of tank inlet to the outlet. NH_4^+ - N in the unplanted systems was relatively high throughout the period of investigation. In both planted and unplanted tanks, NO_3^-N concentrations were very low at the inlets and increased only slightly towards the outlets. Although the presence of *Phragmites australis* had a significant effect on N concentrations at all depths and along the length of the tanks, the nutrient distribution followed the same trend as in unplanted tanks.

Arias, *et al*[30] evaluated the P-removal capacities of different sands for use as media in RZTS. The P- removal capacities were evaluated in short term isotherm batch experiments as well as percolation experiments in absence of plant, mimicking the P-loading conditions in RZTS. The P-removal capacity of the sands of different geographical origin varied considerably and the suitability of sands for use as media in RZTS differed. The P removal capacity of some sands will be used up after only a few months whereas that of others will persist for a much longer time. It was suggested that a quick method for screening of potential media for P-removal is to perform isotherm batch experiments.

Brix, *et al*[31] conducted various experiments for media selection for sustainable P removal in RZTS. The P-binding capacities of light expanded clay aggregate (LECA), crushed marble, diatomaceous earth, vermiculite and calcite media were tested. Particularly calcite and crushed marble were found to have high P-binding capacities. It is suggested that mixing one of these materials into the sand or gravel medium can significantly enhance the P-sorption capacity of the bed medium in RZTS.

Davison, *et al.*[32] summarized the results of studies on four RZTS. The RZTS with gravel media were planted with *Phragmites australis* and were subjected to a variety of effluent types. N removal efficiency observed to be 38% to 66% and that of P was 42% to 70%. Treatment performance (particularly for TN) was found to be negatively correlated with rainfall during their study. They also claimed that the system saturates after eight years operation and further P removal is not possible. Occasionally, P concentration may exceed inlet concentration after this period.

Wallace[33] reported that most of the standard wetland systems do not supply enough oxygen to allow nitrification to occur. The systems are well suited for denitrification to occur because of predominance of reducing environment. He suggested use of cyclic fill and drain systems, advanced wetlands to enhance oxygen transfer, vertical flow wetlands, and paired vertical/subsurface flow systems for effective N removal.

Arias, *et al*[34] found RZTS unsuitable for P-removal. According to them, the only sustainable process for P removal is binding to the bed medium as plant uptake can be neglected in long term. Even if a medium of high binding capacity is selected, its binding capacity will be used up after a few years.

Bayley, *et al* [35] studied influence of depth, HRT and prenitrification on nitrogen removal from domestic effluent using RZTS planted with *Phragmites australis* in 10mm diameter gravel. They achieved 58% total nitrogen (TN) removal under the HLR of 22mm/day and HRT of 10.5 days. They could also notice varied rates of nitrification and denitrification along the depth of the reactor bed. The TN concentration found to decline steadily in all layers up to HRT of 8.7 days.

Browning and Greenway [36] investigated suitability of the native species *Baumea, Carex, Philydrum and Schoenoplectus*, in combination with 5 to 20 mm gravel for subsurface constructed wetlands in Brisbane, Australia. They used pilot scale system receiving secondary treated effluent at HLR of 12 cm/day. The field trial has shown that *Carex* in combination with 5 mm new gravel is the most suitable species among all four species trialed accounting 11% of N removal and 3% of P removal, for use in RZTS.

Picard, *et al*[37] investigated the seasonal efficiency of wetland macrophytes to reduce soil leachate concentrations of TN and TP in experimental RZTS (microcosm). Each microcosm contained one of the following vegetation treatments: unplanted, planted with one of four species (*Carex lacustris, Scirpus validus, Phalaris arundinacea and Typha latifolia*) in monoculture or planted with an equal abundance of all four species. Microcosms exhibited a typical pattern of seasonal nutrient removal with higher removal rates in the growing season and lower rates in the winter months. In general, planted microcosms outperformed unplanted microcosms. Among the plant treatments, *Carex lacustris* was the least efficient. The four remaining plant treatments removed an equivalent amount of nutrients.

Zhang, *et al* [38] conducted glasshouse experiment to test the feasibility of using ornamental wetland species in constructed wetlands to remove nutrients (N and P) from secondary treated municipal wastewater and the potential of different species in mixculture. Ten emergent wetland plants, including six ornamental species: *Canna indica, Lythrum sp., Alocasia macrorrhiza, Zantedeschia aethiopicia, Iris louisiana, Zantedeschia sp.*, and four native rush species: *Carex tereticaulis, Baumea juncea, Baumea articulata* and *Schoenoplectus validus* were planted in microcosm and fed a synthetic wastewater solution in concentrations similar to the secondary treated municipal wastewater. Significant differences among species in accumulations of N and P were detected in both above and below ground tissues, with highest being in *Alocasia macrorrhiza*. In addition, significant differences of pH and dissolved oxygen (DO) were found in the effluents. The highest pH was recorded in the effluent from microcosm containing *Schoenoplectus validus* and the lowest in the effluent from microcosm with *Canna indica*. The highest DO was also found in the effluent from microcosm containing *Canna indica*. It was suggested that *Schoenoplectus validus* and *Canna indica* might be two suitable species to test in mixed culture in the constructed wetland for more efficient use and removal of both N and P from the wastewater.

For ammonia removal in RZTS, three design models are available in EPA Manual[39]. The WPCF Manual of Practice presents a model for ammonia removal based on a regression analysis of RZTS for annual average conditions with no provision for temperature correction.

$$A_s = \frac{0.01Q}{1.527\,ln\,NH_e - 1.05\,ln\,NH_0 + 1.69} \;.....(Eq.2)$$

Where, A_s : RZTS surface area for ammonia removal, ha; NH_e: effluent ammonia, mg/L; NH_0 : influent ammonia, mg/L; Q: average flow through system, m^3/d.

Based on pilot scale work with RZTS, Bavor[39] has presented the following model.

$$A_s = \frac{Q(ln\,NH_o - ln\,NH_e)}{K_t Dn} \;.................(Eq.3)$$

Where A_s: required surface area, m^2; $K_t = K_{20}\,1.03^{T-20}$, K_{20}= 0.107 day^{-1}; D: average depth of liquid in the bed, m; n: effective porosity of bed media, % as decimal; Q: average flow through system, m^3/day.

Hammer and Knight[39] have proposed the following model based on limited number of RZTS.

$$A_s = \frac{0.001831 NH_o Q}{NH_e + 0.16063} \;..............(Eq.4)$$

Where, A_s: RZTS surface area for ammonia removal, ha; NH_e: desired effluent ammonia, mg/L; NH_0: influent ammonia, mg/L; Q: average flow through system, m^3/d.

Discussion

The first RZTS were used at Earby, Yorkshire, UK during 1903[20]. The operating data based on their work was used to develop new RZTS. In India, the technology was used somewhere during 1993-94 and is yet to be established. In this context, as far as usage of RZTS in Indian conditions is concerned, India is quite behind as compared to western countries. However, depending on experience of other countries, RZTS seems to be an attractive option for nutrient removal from domestic wastewater. In this context, many scientists, both in India and abroad, have been working on this technology to understand the process and amend such systems for its wide acceptance. But there is considerable variation among the conclusions drawn. The nutrients removal performance ranges from negative to greater than 90% depending on locality, season and designed configuration. The sizes of RZTS as well as plant and media configuration employed by the researchers seem to affect the conclusion either way, e.g. Winter and Kickuth[14] reported 98% P removal in their plant and soil system, whereas Cooper[15], Arias, *et al*[34] found RZTS unsuitable for P removal. According to Winter and Kickuth[14] and Arias, *et al*[34] plant uptake is negligible but Rogers, *et al*[17] reported plant uptake as a main removal process. Armstrong, *et al*[40] found oxygenated zone in 6-8 weeks at rhizosphere of *Phragmites australis* whereas according to Hiley[20] and Wallace[33], plants do not provide oxygen in rhizosphere. Maehlum[23] reported 60-90% removal at 800 mm rainfall whereas Davison, *et al*[32] found wetland performance negatively correlated with rainfall. Though such reports are site-specific and based on individual's experience, in the absence of comprehensive widely accepted data, the available information leads to misinterpretation and may hamper overall acceptance of this technology.

The performance standards developed in other countries may not be applicable in India for the development of RZTS as climatic conditions, wastewater composition, treatment process and effluent standards differ. The technology should not be taken as "Black Box" as the nutrient removal reactions are dependent upon temperature, pH and oxygen availability. The RZTS performance may also differ according to filter media characteristics[30], plant uptake[17], plant growth and their ability to develop microbial colonies on root surface and in rhizosphere.[41,42] In this context, much attention should be paid to individual component of RZTS, such as its individual plant specie, potential of media, and their combined mechanism for nutrient removal.

The RZTS are characterized by plantation of wetland vegetation. *Phragmites australis* is the most commonly used wetland specie in most of the studies. However, the individual specie may have different potential for nutrient removal depending upon its uptake, growth pattern, size of supporting bed material[36], oxygenation ability, nature of wastewater and season[37]. Even individual specie can alter pH and dissolved oxygen level of the wastewater being treated [38], which may considerably affect nutrient removal mechanism. In this context, there is necessity of identification of wetland plants which would be compatible with selected filter bed material and perform better for nutrients removal.

Various bed materials have been subsequently assessed, as clogging problems were experienced with traditional soil bed media[15], giving consideration to short circuiting of flow patterns in between inlet and outlet structures, pond formations at intermediate levels, clogging of root zone, etc. Many of the studies also concentrated on selection of bed media based on their P sorption capacity [14,30,31,34,43]. However, compatibility of such materials with the growth of specific plant species has not been studied to much extent. Also the combined effect of media size and specific wetland specie on nutrient removal has not been studied extensively. Thus, comparative data among different plant and media combinations under similar conditions is still sparse. It is obvious that size and surface nature of the media will offer different sites for adsorption and biofilm development. The growing roots will occupy different volumes depending on porosity of the media. The dense root system may also interfere with designed flow path[24]. The surface available for development of bacterial colonies by the roots will depend on their extent and may vary from plant to plant. The porosity of the media and occupancy of the roots will ultimately affect HRT. Thus, every plant and media combination may have different treatment potential. In order to extract maximum treatment potential from RZTS, plant and media combination is critical. In this context, combination specific study is required to know treatment potential of RZTS better.

In consideration to the nutrient removal mechanisms in RZTS, basic understanding of the role of each of its components in the removal is not much clear and there is no phenomenal consensus. The mechanism should obviously be different for nitrogen and phosphorus, and also may depend on site-specific variables such as RZTS configuration, wetland plant, bed media and hydrology. In addition to these factors, climatic factors may also have substantial impacts on nutrient removals within constructed wetlands. If these factors are not taken into account, RZTS may prove to be unreliable or unpredictable system for nutrients removal. Thus, it is necessary to evolve sound methodologies which will help for clear understanding of involved mechanism.

The use of equations 1, 2, 3 and 4 [13,39] for the design of RZTS results in variable surface area required for the treatment. This may lead to confusion regarding the area to be adopted for desired nutrient removal. In fact, the design criteria and other parameters that affect system performance should be based on both laboratory and field studies with due consideration to economical and environmental impact assessment. Identification of nutrient inducing sources, establishment of full-fledged treatment plants, understanding the real performance in field conditions, deciding maintenance strategies and optimization of design configuration based on actual experience are few of the issues which will attract subsequent consideration to foster the technology.

Conclusion

CWTS seems to be an attractive option for the abatement of nutrient induced pollution in India. Compared to the use of RZTS abroad, the acceptance and development of this technology is relatively poor in India. The relevant gap can be bridged if the ongoing technical research is directed to identification of wetland plants, supportive bed materials, their combination specific comparative performance under similar conditions and their associated mechanism for nutrients removal. The development strategy should give due consideration to the contributions of other countries so as to avoid unnecessary repetition of work, which will in turn save time, money and efforts, and will help for the real acceptance of RZTS for Indian conditions.

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