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Comparison of Different Types of Media for Nutrient Removal Efficiency in Vertical Upflow Constructed Wetlands

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Abstract

This study investigated the efficiency of two types of media, namely, gravels and sand for their nutrient removal capabilities from wastewater. Different levels of sand depths were also experimented for their removal efficiencies. And for this purpose three laboratory scale vertical upflow constructed wetlands (S1, S2, S3) were established at PHE Laboratory, MNIT, Jaipur. S1was filled with two layers of different size of gravels while S2 and S3 also contained different depths of sand along with the layers of gravels. All the lab scale CWs were fed with the secondary treated water brought from sewage treatment plant, Jaipur. The study was carried out for a period of three months from February to April, 2013. The results show that sand provides better removal of nutrients from wastewater than gravels, though TKN removal was better with gravels. Both sand and gravel were unable to remove NO_3-N from the system as there was an increase in NO_3-N in the system. But overall it can be concluded that sand provided more efficient treatment than gravels.

Keywords: Vertical upflow constructed wetlands, nutrient removal, sand, gravel, Canna indica, tertiary treatment.

1. Introduction

Constructed wetlands (CWs) are human made basin based on various engineering design. They provide ecological condition same as natural wetlands for treating wastewater in different physical, chemical and biological conditions (Sayadi, et al. 2012). High quality effluent water is crucial for reducing the damage caused by releasing treated wastewater into different water bodies. Also, the quality of the treated wastewater is important to the state like Rajasthan, India that has limited water resources and use treated wastewater for irrigation. Due to the dwindling supply of fresh water, Ministry of Environment and Forestry (MoEF), India has provided some standards for nutrient removal from wastewater.

S. No.	**Parameter**	**Standard**	
		Inland Surface Water (mg/L)	**Land for irrigation**
1.	Ammonical nitrogen (as N), mg/l, Max.	50	---
2.	Total Kjeldahl nitrogen (as N), mg/l, Max.	100	---
3.	Dissolved Phosphates (as P), mg/l, Max.	5	---
4.	Nitrate nitrogen (as N), mg/l, Max	10	---
5.	Chemical Oxygen Demand, mg/l, Max.	250	---
6.	pH	5.5 to 9.0	

Vegetation in wetland plays an important role in CW but size and surface nature of the media also provides additional sites for adsorption of nutrients and biofilms development. A major factor in the performance of constructed treatment wetlands is the hydraulic conductivity of the substrate. Hydraulic retention time of the wetland system is dependent on the hydraulic conductivity. Thus, maintenance of hydraulic conductivity is must (Sundaravadivel M. 2003). The main parameter influencing the soil hydraulics is the grain-size distribution (Stottmeister, et al. 2003). Wetland systems with fine- and soil- based substrates will have low hydraulic conductivity, while coarse sand- and gravel- based medium display higher conductivity (Sundaravadivel M., 2003). Experience in Germany and long-term studies of the hydraulics of constructed wetlands with different soil parameters indicate that a mixture of sand and gravel produces the best results in terms of both hydraulic conditions and the removal of contaminants (Stottmeister, et al. 2003).

Plant uptake, substrate adsorption and ammonia volatilization are the type of nitrogen removal mechanism but are generally of less importance. Biological nitrification–denitrification is usually the most significant nitrogen removal mechanism in CWs. (Fenxia Ye 2009). But plants provide environment in the root zone for nitrification-denitrification to occur (Reddy K.R. 1997). The main P-removal mechanisms are adsorption on media and precipitation reactions. Biological assimilation and plant uptake has a very little role in phosphorus removal. Since harvesting plants contributes very little to phosphorus removal from CW, therefore media play a major role in phosphorus removal (Dong Cheol Seo 2005). In sand or gravel substrates, phosphorus is bound to the media mainly as a consequence of adsorption and precipitation reactions with Ca, Al and Fe. At pH levels greater than 6, the reactions are a combination of physical adsorption to iron and aluminium oxides and precipitation as sparingly soluble calcium phosphates. At lower pH levels, precipitation as iron and aluminium phosphates (strengite, variscite) becomes increasingly important. The capacity of filter media to remove P may therefore be dependent on the contents of these minerals in the substrate (Vohla Christina 2011).

In the gravel systems, (Tanner 1999) showed P accumulation decreased and substratum P-sorption capacity became saturated in 5 years. (Korkusuz 2005) showed for domestic wastewater treatment in Turkey, vertical subsurface flow constructed wetlands showed TP removal efficiency for gravel wetland cells of only 4%. (He 2007) reported TP removal during a 14-weeks experiment in a gravel wetland from 6.8% to 54%, on average 22.44%. In pilot-scale units containing medium gravel obtained from a quarry, (Akratos 2007) found greater removal efficiency for fine gravel (89%), followed by medium gravel with cattail (67%) and cobbles (57%). The removal efficiencies of the other two units were significantly lower (medium gravel with reed 28.2%; medium gravel alone 43.9%). $PO_4{}^{3-}$ and TP removal efficiency was predominantly affected by porous media size and type. (Arias 2001) found that the P-removal capacity of some sands would be used up after only a few months in full-scale systems, whereas that of others would persist up to several years. The most important characteristic of the sands that determined their P-removal capacity was their Ca content. (Pant 2001) showed that some local sands from Canada with elevated contents of Fe, Al and Ca have high P sorption capacity. Sand filters are also known as efficient units for complex wastewater purification (BOD, COD, NH4-N, and also in some cases PO_4-P and fecal coliforms).

Many of the studies concentrated on selection of bed media based on their sorption capacity. But, every plant and media combination may have different treatment potential. In order to extract maximum treatment potential, plant and media combination is critical. However, not much of the research work has been done on this point. The following points reveal the areas where the research is lacking.

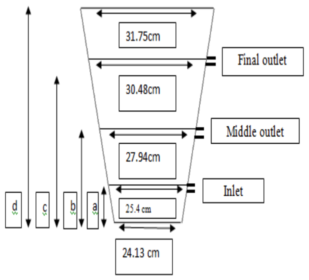
- Compatibility of medium materials with the growth of specific plant species has not been studied to much extent.
- Also, the combined effect of media size and specific wetland species on nutrient removal has not been studied extensively.
- Comparative data among different plant and media combinations under similar conditions is still sparse.

The purpose this study was to investigate the nutrient removal efficiency of two types of media namely, sand and gravels. The specific objectives were: 1) To examine and compare the efficacy of sand and gravels for N, P, K removal, 2) To identify and compare the different depths of sand medium for better N,P,K removal, 3) To examine and compare the NH_4-N and NO_3-N removal at two different heights of the vertical upflow constructed wetlands and 4)To examine other parameter like pH, alkalinity and COD.

2. Material & Methods

The study was performed on three vertical up-flow constructed wetlands (namely S1, S2, S3) located outside the PHE Laboratory, Department of Civil Engineering, MNIT, Jaipur. The experimental analysis was carried out at PHE Lab, MNIT, Jaipur and Agricultural Research Lab, Durgapura, Jaipur for a period of three months from February to April, 2013. All the reactors were fed with secondary treated wastewater obtained from STP, Jaipur.

The experimental set up was comprised of three trapezoidal plastic tank of volume 20 L each; provided with three outlets. The dimensions were 0.70 m length and width at inlet, middle outlet and final outlet was 0.254m, 0.279m and 0.305m respectively. The total area of each reactor was 0.176m^2. The three opening for inlet, middle and final outlet are at the depth of 0.635m, 0.3556m, and 0.5842m respectively. Each system was fitted with a broad crested weir at the bottom which was meant to equally distribute wastewater. The treatment zone depth in each system was 0.5842m. The flow rate was maintained at 8.64L/day with the help of peristaltic pump. The reactor S3 was established on 31st December, 2012 while rest two were established a year ago.



System	Vegetation	Medium
S1	Canna indica	Gravel
S2	Canna indica	Gravel & Sand *
S3	Canna indica	Gravel & Sand *

*depth of medium is different in S2 & S3

(a) **(b)**

Fig 1: (a)Schematic diagram of reactor, where a=6.35cm; b= 35.56cm; c= 58.42cm; d=70cm. (b)Type of vegetation and media.

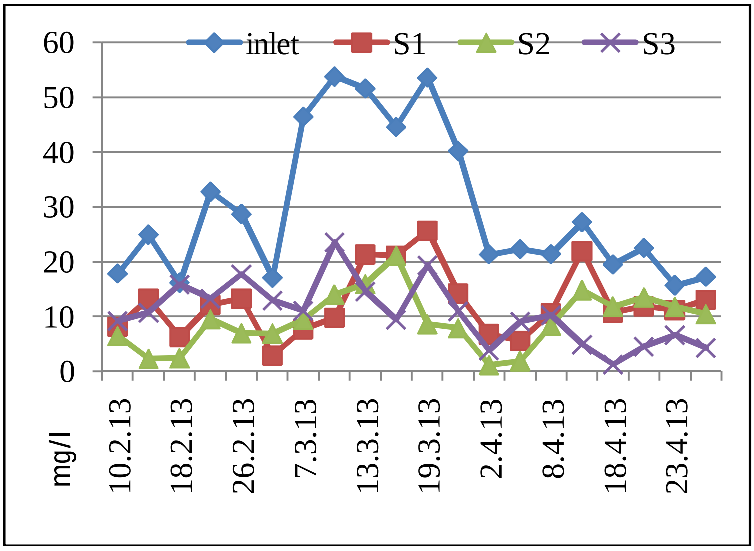
Fig. 2: Storage tank; S1, S2, S3 planted with Canna indica but had different gradation of media.

The samples were taken twice a week and were immediately analyzed for NH_4-N, NO_3-N, TKN, PO_4, potassium, pH and alkalinity. (APHA, Standard Methods for the Examination of Water and Wastewater 1999).

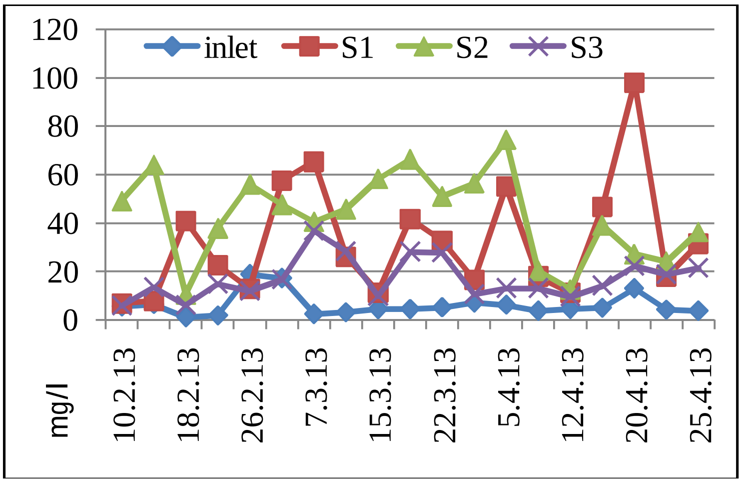
3. Results

3.1 NH_4-N Results (At Final Outlet)

The removal efficiency of S1, S2 and S3 was 58.41%, 68.91% and 64.14% respectively. The fine grained soils always show better nitrogen removal through adsorption than the coarse-grained soil. The higher elimination rate can be explained by the higher cation exchange capacity of the fine grained soils (J. Vymazal 2005). This explains the removal efficiency of S1, S2 and S3 because S1 contained gravels while S2 and S3 contained gravels along with sand. Although S3contained larger depth of sand than S2 but provided less treatment. This difference in treatment of S2 and S3 can be due the fact S3 is newly established system. It might take some time to get stabilized though the treatment is almost the same as S2. This somewhat less treatment might be due to the fact the microbial layer was not properly developed in it and the roots of the plant might not have extended deep enough. From the graph (1), it can also be seen that in the last week of analysis S3's removal efficiency had increased. So, it can be inferred that the system had been stabilized in four months. According to MoEF standards, NH_3-N of maximum 50 mg/L is allowed for inland surface water disposal. The effluents from all the three wetland systems were below the MoEF standards so they can be disposed off into inland water and can be used for irrigation as well.



Graph 1: Comparison for NH_4-N removal.



Graph 2: Comparison for NO_3-N removal.

3.2 NO_3-N Results (At Final Outlet)

The average NO_3-N influent was 6.25 mg/L and the average NO_3-N effluent of S1, S2 and S3 was 32.70 mg/L, 42.96 mg/L and 17.06 mg/L. The percent increase in nitrate S1, S2 and S3 was 80.88%, 85.45% and 63.37% respectively. The increment in NO_3-N in S2 as compared to S1 can be explained by fact that S2 provided more sites for ammonium adsorption than S1. So when these ammonium ions came in contact with oxygen, they got oxidized to NH_4-N. Sand also decreases the hydraulic conductivity of the wastewater so increases the time for treatment. Now, when S2 and S3 were compared the result contradicted with the expected result. The depth of the sand medium in S3 was larger as compared to S2, so it was obvious that it provided more adsorption sites for ammonium ions and more time for treatment. But, the fact that S3 was newly established, the root growth and microbial layer might take some more time to make the system work efficiently. According to MoEF standards, NO_3-N of maximum 10 mg/L is allowed for inland surface water disposal. The effluents from all the three systems had higher concentration of nitrate nitrogen than recommended by MoEF so effluent wastewater from them cannot be disposed off into inland waters but can be used for irrigation.

3.3 Middle Outlet NH_4-N Results

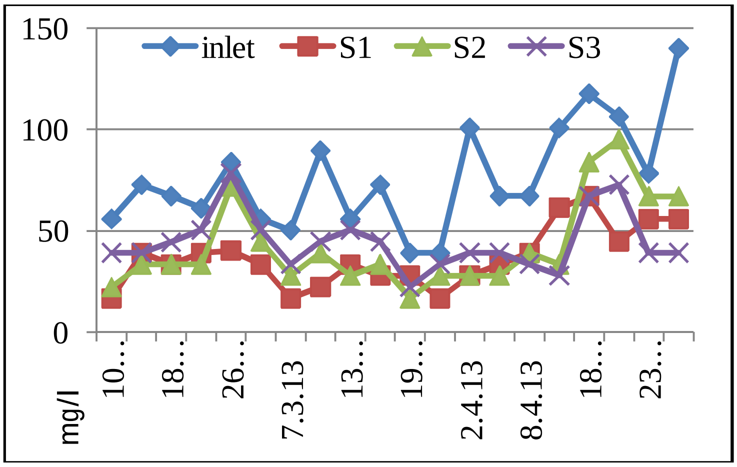
The experimental analysis for middle outlet effluent was done for 6 days only. With 6 days data it was observed that the removal efficiency at middle outlet of S1, S2, and S3 was 18.14%, 4.54% and 4.57% respectively at middle outlet and 33.17%, 40.57% and 73.20% respectively at the final outlet. S1 was filled with a thick layer of one type of gravel only while both S2 and S3 were filled with two layers of different gravel sizes. This configuration was up to the middle outlet. The results were somewhat contradicting in the sense that as the size of the gravel decreases, the NH_4-N removal should increase because the surface area for adsorption increases. But the possible explanation of the present result can be the larger pore size of the gravels in S1 which provided better and uniform colonization of microorganisms and more oxygenation. The results of S2and S3 are same since they have same configuration till middle outlets. The results of S2 and S3 at the final outlet showed better removal because of the presence of sand above the middle outlet in both the system. Presence of sand reduced the hydraulic conductivity and increased the duration for adsorption of NH_4 ions in S2 and S3 hence provided better removal. Presence of plants near the final outlet is also one of the beneficial factors.

3.4 Middle Outlet NO_3-N Results

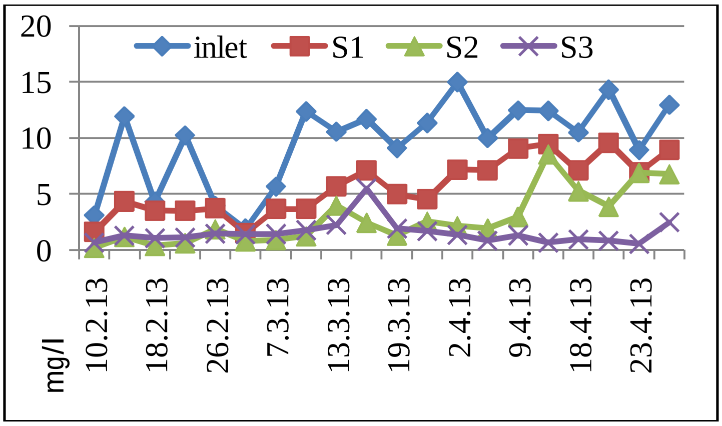
The percent NH_4-N removal of S1, S2 and S3 was 18.14%, 4.54% and 4.57% respectively at middle outlet. And the percent NO_3-N removal of S2 and S3 was 27.81% and 13.23% while there was 29.98% increase in NO_3-N in S1. These results clearly show that S1 is very well aerated because NH_4-N got oxidized to NO_3-N and a good amount of nitrification occurred in the system. Contrast to this, in S2 and S3, NO_3-N removal occurred which shows that both the systems are less oxygenated in comparison to S1. S1 comprised of a layer of 16-20mm gravels while S2 and S3 were filled two different layers of gravels till the middle. And this could be the possible reason of less oxygen in S2 and S3. S1 had larger and uniform pores so better oxygen transfer occurred in it. S2 provided better nitrate nitrogen removal than S3 though they both had the same configuration till the middle point. This is because microbial film in S2 is well developed than S3 as S3 was only four months old system.

3.5 Total Kjeldahl Nitrogen (TKN) Results

The removal efficiency of S1, S2, and S3 are 51.75%, 43.42% and 41.55% respectively. The average influent TKN was 76.14 mg/L and average effluent TKN of S1, S2 and S3 were 36.37 mg/L, 42.80 mg/L and 44.60 mg/L respectively. These results show that TKN removal greatly depends on the porosity of the media. As the porosity of media increases, the oxygen transfer across the media increases and hence TKN removal also increases. Gravels provide better adheration sites for microbial layer than sands which provided better mineralization of organic nitrogen and oxidation of ammonium ions. According to MoEF standards, TKN of maximum 100 mg/L is allowed for inland surface water disposal. The effluents from all the three wetland systems were below the MoEF standards so they can be disposed off into inland water and can be used for irrigation as well.



Graph 3: Comparison for TKN removal.



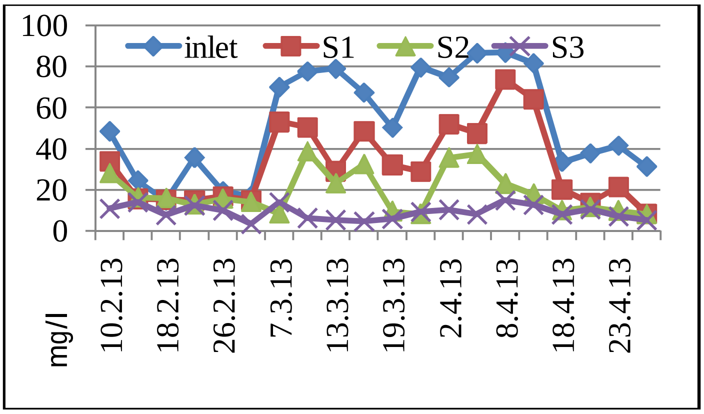
Graph 4: Comparison for phosphorus removal.

3.6 Phosphorus (as orthophosphate) Results

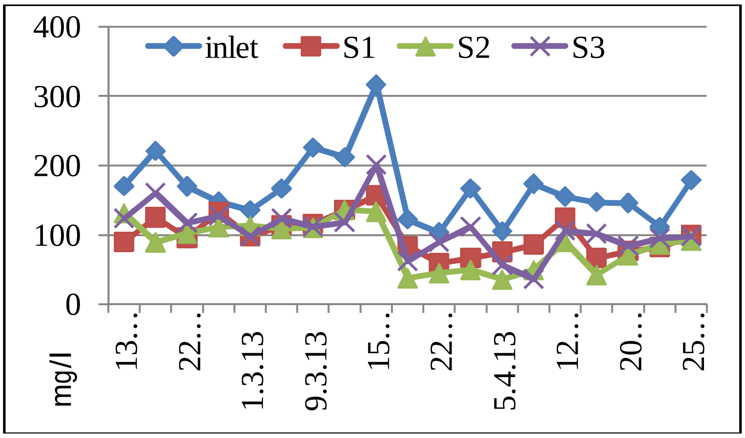
The removal efficiency of S1, S2and S3 is 41.10%, 70.80% and 83.93% respectively. The average influent phosphorus was 9.64 mg/L and the average effluent phosphorus of S1, S2 and S3 was 5.68 mg/L, 2.81 mg/L and 1.55 mg/L respectively. It is well known that fine grained soil has better phosphorus removal abilities as they have greater surface area to provide better adsorption. The results of the present study very well relate to this theory. S1 had only gravel medium while S2 and S3 had gravel medium as well as sand medium. Thus, increase in the thickness of the sand layer had proved beneficial for the phosphorus removal. According to MoEF standards, dissolved phosphates of maximum 5 mg/L is allowed for inland surface water disposal and the effluents from only S2 and S3 wetland systems were below the MoEF standards so they can be for inland water disposal and for irrigation as well. The effluent from S1 can only be used for land for irrigation.

3.7 Potassium results

It is noteworthy that in the literature, there is not much information on potassium removal in wetlands with which to compare the findings of this study. Potassium is an essential element in both plant and human nutrition, and occurs in ground waters as a result of mineral dissolution, from decomposing plant material, and from agricultural runoff. The common aqueous species is K^+. Unlike sodium, it does not remain in solution, but is assimilated by plants and is incorporated into a number of clay-mineral structures. It is one of the macro nutrients for plant growth. The removal efficiency of S1, S2 and S3 were 38.19%, 64.24% and 82.94% respectively. From these results it can be explained that potassium removal occurred both due to plant uptake and adsorption to the media. S2 and S3 had more adsorption sites than S1. One more thing that can be inferred from these results is that increasing the depth of sand medium gave almost the same amount of removal although the concentration of potassium in influent had increased.



Graph 5: Comparison for potassium removal



Graph 6: Comparison for COD removal.

3.8 COD

The organic matter in wastewater are degraded both anaerobically and aerobically by heterotrophic microorganisms in the wetland reactors depending on oxygen concentration in the bed (Soon-An Ong 2009). The total removal efficiency of S1, S2 and S3 is 40.88%, 48.56% and 36.38% respectively. The average influent COD was 166.9 mg/L and the average effluent COD of S1, S2 and S3 was 98.66 mg/L, 85.85 mg/L, 106.18 mg/L respectively. The difference in COD removal efficiency of S1 and S2 is due to presence of gravel and sand medium in the system. Filtration, which is an important process in the removal of COD imparting wastewater constituents, is effected well by sand. Sand can even remove such small materials as pathogenic bacteria in water. This is the reason the S2 provided better COD removal. S3 provided the least COD removal because this system is new as compared to others. The possible reason of less treatment is that microbial layer in the system is not fully developed. According to MoEF standards, COD of maximum 250 mg/L is allowed for inland surface water disposal. The effluents from all the three wetland systems were below the MoEF standards so they can be disposed off into inland water and can be used for irrigation as well.

3.9 Alkalinity and pH Results

The average influent pH and alkalinity was 8.5225 and 474.4. The average effluent pH of S1, S2 and S3 was 8.417, 8.491 and 8.492 respectively and the average effluent alkalinity of S1, S2 and S3 was 576.53, 451.46 and 502.13 respectively. As it can be seen that pH of the effluent has not decreased much and there is an increase in the alkalinity in almost all the three systems. The increase in the alkalinity in S3 and S2 can be contributed to simultaneous nitrification and denitrification in the system. In S1, nitrification is the major process but microbial layer respiration adds CO_2 in the water which forms bicarbonate ions and in turn increases the alkalinity. Calcium generally is the prevailing metal in the natural sands and high pH of domestic sewage, favor precipitation reactions with Ca in the medium. The pH of the effluent between 7.5 and 8.5 favors the chemical precipitation of the various forms of calcium phosphates (Vohla Christina 2011). This also indicates that precipitation reactions with Ca were one of the processes responsible for the removal of phosphorus in the sands studied. The precipitation reactions could lead to increasing pH but increase in alkalinity acts as buffering agent and maintains a stable pH of the wastewater.

4. Conclusion

This study showed that sand in the system did not provide better oxygenation throughout the system, while gravels did. But, it did provide better adsorption sites for ammonium, phosphate and potassium ions. It also proved good for filtration of organic matter. Calcium ion dissolution from sand helped in better phosphorus removal. However, gravels provide better adheration sites for microbial layer. Plantation helped in better oxygenation of the system but it did not allow nitrogen removal from the system. Increase in nitrate in planted vertical upflow constructed wetland leaves the wastewater unhealthy for inland surface disposal as it would cause eutrophication. But this water can be used for irrigation and would decrease cost of fertilizers. Use of locally available sand increased the phosphorus removal and would also decrease the cost of medium when applied in full scale constructed wetlands.

5. Acknowledgement

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