Performance of Filterbeds and Macrophytes in Vertical Constructed Wetland for Treating Domestic Sewage Effluent

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Abstract

An experiment with different filterbeds and macrophytes was carried-out to study their phytoremediation capacity on the efficiency of domestic wastewater treatment through constructed wetland (CW) during November to March, 2017-18 at University of Agricultural Sciences, Dharwad campus, Karnataka, India. Twenty treatment combinations involving five types of filterbeds (FB-1: *gravel*, FB-2: *gravel-sand-gravel*, FB-3: *gravel-sand-brick-gravel*, FB-4: *gravel-sand-charcoal-gravel* and FB-5: *gravel-sand-(charcoal+brick)-gravel*) and four macrophytes (MP-1: *Typha latifolia*, MP-2: *Brachiaria mutica*, MP-3: *Canna indica* and MP-4: *Phragmites* spp.) were evaluated for treating domestic wastewater. After 120 days from start, across treatment combinations, water electrical conductivity (EC), total dissolved and suspended solids (TDS-TSS), biological oxygen demand (BOD), chemical oxygen demand (COD), sodium, sodium adsorption ratio (SAR), residual sodium carbonate (RSC), bicarbonates, total nitrogen-phosphorus-potassium (N-P-K) and boron (B) were reduced by more than 40 per cent due to wetland treatment. The system enhanced the mineralization of organic nitrogen to ammoniacal nitrogen ($\text{NH}_4^+\text{-N}$) and nitrate nitrogen ($\text{NO}_3^-\text{-N}$) fractions. Among filterbeds, Type-5 caused higher reduction in pH, EC, BOD, COD and Organic-N while, Type-4 proved efficient in removing total solids and lowering pH in the sewage effluent. The Type-3 filterbed removed more suspended solids, potassium and ammoniacal nitrogen. Among the macrophytes, *Brachiaria* (paragrass) removed more nitrogen and potassium while, *Phragmites* removed more nitrogen, phosphorus and boron. The flexibility of implementation allows the CW to be adapted to different sites with different configurations, being suitable as main, secondary or tertiary treatment stage.

Novelty And Impact Of Study

Enormous quantity of sewage water is generating in major cities of India. Only portion of this is being treated with conventional sewage treatment plants, which are very expensive, need energy and require regular maintenance. Usually, the untreated sewage water is drained to natural streams where it is directly used by farmers for crop production. The direct use of sewage water is detrimental to both soil and crop and in turn human health. Globally, efforts are made to refocus on approaches to treat wastewater and reuse it for irrigation and different purposes. This will overcome local water shortfalls and also serve as nutrient resource.

Wastewater treatment technology needs to be appropriate and sustainable. It also needs to be less costly, easy to operate and maintain, and very efficient in reducing organic and nutrient load, increasing oxygen supply and removing heavy metals. Such wastewater treatment technologies should integrate natural processes which are eco-friendly and cleanse water as it flows through rivers, lakes, streams, and wetlands in nature.

The choice of filterbed materials and their vertical arrangement is the key in maximizing the efficiency of physical filtration system and minimizing the treatment cost. Inclusion of a suitable macrophyte in the system is reported to enhance the efficiency of the wetland system. Keeping these in mind, the present study (column study) was carried-out with locally available filterbed materials (*viz.* gravel, sand, charcoal and brick) and macrophytes (*Typha latifolia*, *Brachiaria mutica*, *Canna indica* and *Phragmites* spp.) for treating the domestic sewage effluent of the Agricultural University Campus.

The findings of this study underscore the development of a low cost constructed wetland using locally available materials and macrophytes for treating domestic sewage water in small towns. This will help in re-use of treated wastewater for crop production especially in water scarce areas.

Introduction

Water, food and energy securities are emerging as increasingly important and indispensable issues for India and the world. Water is vital yet, a constrained resource in most of the developing nations. The average availability of potable water is dwindling steadily and India may become a water-scarce country by 2025. Thus, recycle and reuse water needs greater attention. About 38,354 million litres per day (MLD) of sewage water is generating in major cities of India. However, the total sewage treatment capacity in these cities is only 22,963 MLD (Annon., 2020). A large portion of this surplus sewage has the potential to cause widespread water pollution.

About 80 countries and regions, representing 40 per cent of the world's population, are experiencing water stress and about 30 of these countries are facing water scarcity during a large part of the year (Kharraz et al., 2012). To compensate for water shortage, many countries have begun exploiting reserves that are not sufficiently being replenished. This short-term strategy is likely to have detrimental long-term effects on the availability of freshwater for human communities and native eco-systems. The consequences of regional and national water scarcity will lead to a depletion of reserves. This scarcity will also give rise to competition for water between nations and regions, as well as among sectors such as agriculture, industry and municipalities.

Globally, agriculture is the dominant user of water, accounting for 70 per cent of total freshwater for irrigation. India's agriculture sector, which is the backbone of Indian economy, right now utilizes around 90 per cent of total water resources. However, with the increasing competition between agriculture, industry and domestic sectors, agriculture is beginning to receive less share of freshwater. Moreover, fast depletion of groundwater reserves coupled with severe water pollution, has placed India in difficult position to provide sufficient freshwater for irrigation. In India, the evident shortage of fresh water coupled with a considerable increase in the volume of urban wastewater production from the growing cities have made the problem worse and difficult to manage.

Sewage irrigation is an age-old farming practice and reuse of wastewater in agriculture is gaining wider acceptance in many parts of the world. Sewage water offers an alternative irrigation water source, as well as the chance to recycle plant nutrients. Wastewater also additionally contains expansive range of taints *viz.*, bio-degradable organic compounds, toxic metals, suspended solids, micro-pathogens and parasites (Montaigne and Essick 2002; Pedrero and Alarcon 2009) which restrict its direct application to field.

In developing nations like India, the issues related with wastewater reuse arise from its lack of treatment. Energy and skill intensive wastewater treatment technologies are most often costlier and not feasible alternatives in areas where electricity supply is scarce and unreliable. The challenge thus is to find such low-cost, low-tech, user friendly methods of wastewater treatment, which on one hand abstain from debilitating our substantial wastewater dependent

livelihoods and on the other hand prevent degradation of our valuable natural resources. It is an advantageous time to refocus on approaches to treat wastewater and reuse it for irrigation and different purposes. Utilization of treated wastewater offers new vistas in improving water accessibility and keeps up water quality prerequisites for crop production (Azize dogan Demir and Ustum Sahin 2017) .

Natural processes have always cleansed water as it flowed through rivers, lakes, streams, and wetlands in nature. In developing countries natural treatment systems are considered more suitable which can be built with locally available materials and thus become cost-effective. Natural treatment systems are considered one of the best treatment options, particularly in warm climates (Duenas et al., 2003). Wetlands with hydrophytes are one of the many types of natural systems that can be used for treatment of municipal wastewater.

The major nutrient removal mechanisms associated with constructed wetland system include biodegradation, precipitation and filtration (Vymazal 2011; Dash 2012). The choice of materials for filterbed and their vertical arrangement, thickness/depth-wise, should aim at maximizing the efficiency of these foresaid processes and minimizing the treatment cost. Keeping these in mind, the present study (column study) was executed with locally available materials such as gravel, sand, charcoal and brick materials as filterbed for treating the domestic sewage effluent.

Materials And Methods

The study was carried out at the Department of Soil Science and Agricultural Chemistry, College of Agriculture, Dharwad, Karnataka from November 2017 to March 2018. The study consisted of 20 treatment combinations of five filterbeds (FB-1: *gravel*, FB-2: *gravel-sand gravel*, FB-3: *gavel-sand-brick-gravel*, FB-4: *gravel-sand-charcoal-gravel* and FB-5: *gravel-sand-(charcoal+brick)-gravel*) and four macrophytes (MP-1: *Typha latifolia*, MP-2: *Brachiaria mutica*, MP-3: *Canna indica* and MP-4: *Phragmites sps.*) with three replications.

The vertical flow wetland was constructed using PVC pipes (100 cm length and 15 cm dia.), supported in position by iron stands. The top 20 cm in each column was left for planting the macrophyte and ponding purposes and the remaining 80 cm height was filled with different filter bed materials (Figure 1). The bottom end of the pipe was closed with end cap fitted with a valve. To facilitate easy entry and surface non-clogging, the top 25 cm layer in all the treatments was filled with gravels (basaltic stone pieces) of ~ 20 mm size. Similarly, the bottom 25 cm was filled with gravel of ~ 20 mm size for free downward discharge. The middle 30 cm in the column (except in '*Gravel*' filterbed where the entire column was filled with gravel) was filled with sole or combinations of different filter bed materials. In '*Gravel-Sand-Gravel*' filterbed, the middle 30 cm was filled with sand (0.02- 2.0 mm). In '*Gavel-Sand-Brick-Gravel*' filterbed, the mid layer was subdivided into two; the top 15 cm filled with sand and the lower 15 cm with brick (~ 20 mm) while in '*Gravel-Sand-Charcoal-Gravel*' filterbed, the top 15 cm was filled with sand and the lower 15 cm with charcoal (~ 20 mm). In '*Gravel-Sand-(Charcoal+Brick)-Gravel*' filterbed, the top 15 cm was filled with sand and the lower 15 cm with the equal (50:50 by w/w) mixture of charcoal and brick material (Figure 1). The physical properties of the filterbed materials are given in Table 1. The hydraulic retention time was worked out using the formula given below:

Hydraulic retention time
(HRT, in days)

Total storage (cc)

Influent flow rate (cc/ day)

The total storage (porosity volume, cc) was calculated from the porosities of the proportionate contents of filterbed materials filled in each column, which differed among filterbed treatments (Table 2). The hydraulic retention time was set uniformly at 2.5 days by regulating Influent flow rate using the valve fitted at the bottom of each column.

The planting materials of all the four macrophytes were collected from waterlogged / marshy areas around University campus, Dharwad and reared in plastic trays with minimum soil. Young plants of macrophytes raised using sand medium were transplanted in the top layer of gravel in each column after washing off the sand adhering to roots. The columns were irrigated with primary treated sewage effluent (PTSE). Every day, the treated water collected in drain-can was decanted and once in 15 days, the treated water was collected and stored in refrigerator for physico-chemical analysis.

The PTSE from the sedimentation tank in the flow stream in the premises of the University was used for this study. The sewage water from this sedimentation tank was collected regularly and fed to the columns to have ponded condition. The quality of this PTSE was monitored at fortnightly intervals while, the treated sewage effluent samples from each column were analyzed at 120 days from the start of the study. The water quality parameters were analyzed following standard methods: pH, EC (Sparks 1996); total phosphorus and BOD (Anon. 1975); COD, sodium, ammoniacal nitrogen, nitrate nitrogen, total nitrogen, SAR, RSC and bicarbonates (Tandon 1998); total dissolved solids, total suspended solids, total solids and boron (Gupta 2007).

The macrophytes were cut/ pruned at 10 cm height from the base at 30 days intervals and dried in hot air oven at 65° C until two consecutive weights were constant. At the end, the total dry shoot biomass of each macrophyte over a period of 120 days was obtained by the summing all the biomass yields of each column and expressed as g column⁻¹. The N, P and K concentration in this dry shoot biomass was estimated as per standard methods (Jackson 1973). The

NPK uptake by plant was worked out using the following equation: (g column⁻¹)

NPK uptake

=

NPK content (%) × Dry matter yield of plant (g column⁻¹)

100

Statistical analysis

The statistical interpretation of the experimental data was done by following the Fischer's variance analysis technique as given by Gomez and Gomez (1984). The experimental data were analyzed as per Factorial CRD to compare among the filterbeds, macrophytes and the interaction between the two. The results were computed at five per cent (P = 0.05) level of significance. Critical differences (CD) were worked out whenever 'F' test was significant and treatment means were compared by applying Duncan's multiple range test (DMRT).

Results And Discussion

The average characteristics of the primary treated sewage effluent (PTSE) is given in Table 3. The pH was moderately alkaline (8.35) with considerable amount of salts (2.0 dS m⁻¹). The effluent had the total dissolved and suspended solids of 1376 and 306 mg L⁻¹, respectively. The BOD (256 mg L⁻¹) and COD (506 mg L⁻¹) were marginally higher than prescribed for direct irrigation. The alkalinity of sewage water was due to higher concentrations of sodium and bicarbonates as indicated by higher residual sodium carbonate concentration (5.56 mg L⁻¹). Among nitrogen forms, ammoniacal nitrogen predominated (13.11 mg L⁻¹) followed by organic nitrogen (10.02 mg L⁻¹) and least was nitrate nitrogen (1.81 mg L⁻¹). The mean total phosphorus and potassium concentrations were 10.30 and 43.03 mg L⁻¹ respectively. The boron concentration was low (0.28 mg L⁻¹).

The physico-chemical parameters of the treated sewage effluent after 120 days from start were assessed for evaluating the performance of filterbeds and macrophytes.

pH

The lowest effluent pH was recorded in '*gravel-sand-(charcoal+brick)-gravel*' filterbed (7.18). Constructed wetland vegetated with *Phragmites* was most efficient in reducing pH compared to other macrophytes (Table 4).

Across treatments, the reduction in pH after 120 days was 11.4% compared to PTSE. Similar observation was made by Rajimol *et al.* (2016). The observed pH reduction was attributed to CO₂ production from decomposing plant litter, dissolved organic matter and other sewage effluent components trapped in the root mat and nitrification of ammonia (Arivoli and Mohanraj 2013). Presence of considerable calcium+magnesium (SAR < 5) in PTSE (Table 3) and its alkaline pH favour precipitation of these alkaline metals as their carbonates and phosphates when it is stranded in the wetland. That might be the reason for general lowering of pH of treated sewage effluents. Similar reasoning was reported by Priya *et al.* (2013). They opined that the effluent pH between 7.5 and 8.5 could be ideal for the chemical precipitation of various forms of calcium phosphates. However, the removal of calcium+magnesium through precipitation was only marginal so that the SAR was not increased rather it decreased possibly due to lowering of sodium also through adsorption on filterbed materials and uptake by macrophytes. The reduction in EC of treated sewage effluent over PTSE supported this fact (Table 3). The presence of brick and charcoal as filterbed materials in addition to sand and gravel might have favoured such reactions.

Electrical conductivity (EC)

The EC values for filterbeds and macrophytes varied only slightly (Table 4). Among filterbeds, '*gravel-sand-(charcoal+brick)-gravel*' reduced more EC and among macrophytes, *Canna* and *Phragmites* recorded low EC values. The constructed wetland with '*gravel-sand-(charcoal+brick)-gravel*' + *Canna* and '*gravel-sand-charcoal-gravel*' + *Phragmites* combination significantly reduced EC (0.67 dS m⁻¹). There was a substantial reduction (50.5 %) in EC compared to PTSE (2.00 dS m⁻¹). The decrease in conductivity was attributed to uptake of micro and macro elements and ions by plants and bacteria, and their removal through adsorption to plant roots, litter and settleable suspended particles (Vera *et al.* 2011 and Arivoli and Mohanraj 2013) and also due to precipitation.

The '*gravel-sand-(charcoal+brick)-gravel*' filterbed caused greater reduction in EC compared to others. Looking to the composition of this filterbed, it seemed presence of charcoal and brick with possible micro-porosities could bring more adsorption of ions and thereby lower EC. Among the macrophytes, *Phragmites* and *Canna* favoured greater reduction in EC. The average EC reduction after 120 days was 50.5% compared to the mean values of PTSE for the same period (Table 3).

Total dissolved solids (TDS)

Among filterbeds, '*gravel*' (742 mg L⁻¹) reduced more TDS whereas among macrophytes, *Brachiaria* (727 mg L⁻¹) was more efficient compared to others (Table 4). The combination of '*gravel*' and *Brachiaria* recorded significantly lower TDS (673 mg L⁻¹). Greater reduction (43.2%) in TDS was observed due to wetland treatments over PTSE (Table 3).

The solid portion may be in suspended, dissolved and colloidal states which impart turbidity to the sewage water. Efficiency of constructed wetland in the removal of turbidity is reported to depend largely on the size of sand/ bedding particles and the depth of the bed (Jing *et al.* 2001).

Total suspended solids (TSS)

The '*Gravel-sand-brick-gravel*' was more efficient in TSS removal among macrophytes while *Brachiaria* among macrophytes (Table 4). The interaction of '*gravel-sand-(charcoal+brick)-gravel*' and *Brachiaria* recorded significantly lower TSS (39 mg L⁻¹). A substantial reduction in TSS (50.7 %) was observed due to wetland treatment over PTSE. The mean reduction in TSS was greater than in TDS. Similar observation was made by Vymazal (2011) who opined that suspended solids are retained predominantly by filtration and sedimentation. The '*gravel-sand-brick-gravel*' filterbed removed more TSS than others. Among macrophytes, *Brachiaria* performed better compared to others in terms of TSS removal. The constructed wetland system acted as a mechanical and biological filter and removed suspended particles from the water (Zurita *et al.* 2009; Vera *et al.* 2011; Suhad *et al.* 2018).

Total solids (TS)

The TS at 120 days varied relatively among filterbeds (901 to 966 mg L⁻¹) and macrophytes (838 to 999 mg L⁻¹). The '*gravel-sand-charcoal-gravel*' among filterbeds while, *Brachiaria* among macrophytes was more efficient in lowering TS (Table 4). The interaction between the filterbeds and macrophytes was significant. The combination of '*gravel-sand-(charcoal+brick)-gravel*' and *Brachiaria* recorded significantly lower TS (744 mg L⁻¹). A considerable reduction in total solids (44.5 %) was recorded over PTSE due to physical and biological filtration processes (Table 3).

Biological oxygen demand (BOD₅) and chemical oxygen demand (COD)

The BOD₅ concentration of treated effluent was significantly reduced due to filterbeds and macrophytes (Table 4). The filterbed 'gravel-sand-(charcoal+brick)-gravel' (92.1 mg L⁻¹) reduced more BOD₅ concentration compared to other filterbeds. The BOD₅ concentration of macrophytes varied slightly in the range of 106-107 mg L⁻¹ though, *Brachiaria* showed statistical superiority over others. The combination of 'gravel-sand-(charcoal+brick)-gravel' and *Canna* recorded significantly lower BOD₅ (88.3 mg L⁻¹).

Among the filterbeds, 'gravel-sand-(charcoal+brick)-gravel' (212 mg L⁻¹) was more efficient in COD reduction compared to others (Table 5). Among Macrophytes, *Canna* (224 mg L⁻¹) topped with higher reduction in COD compared to others. The COD concentration of macrophytes ranged from 224 to 231 mg L⁻¹. The interaction of 'gravel-sand-(charcoal+brick)-gravel' and *Canna* significantly reduced COD in treated sewage effluent (208 mg L⁻¹).

Compared to the average BOD concentration of PTSE, the reduction in BOD was 58.6 % due to constructed wetland treatments (Table 3). As like in case of BOD, the COD reduction was 55.3 % due to wetland treatment over PTSE. Similar reductions through wetland were also reported by Jizheng *et al.* (2012). Based on the mean BOD value of 256 mg L⁻¹ (Table 3), the raw sewage effluent was unsuitable for irrigation when compared to permissible limits of 100 mg L⁻¹ (Anon. 1985). After allowing the raw sewage effluent to flow through wetland system, there was a reduction in its BOD₅. Zurita *et al.* (2009) reported a higher BOD₅ removal efficiency in a vertical flow constructed wetland system because of the better oxygen transfer from the atmosphere. The presence of multiple plant species as a bio-filter with varied root-phenotypic traits has been reported to provide a more propitious habitat for the development of a great microbial diversity leading to higher removal efficiencies. Similar findings were reported by Li *et al.* (2008), Vera *et al.* (2011) and Kelvin and Tole (2011). The same reason could be attributed to the notable decline in the COD of treated sewage effluent since both COD and BOD measures the organic matter present in sewage effluent and the same principles of removal inside the constructed wetlands would apply to them. The reduction of COD might be due to higher dissolved oxygen in rhizosphere meeting the oxygen demand for chemical oxidation of organic constituents. According to MoEF standards, COD of maximum 250 mg L⁻¹ is allowed for inland surface water disposal and as well for irrigation. In the present study, the treated effluent COD was reduced to less than 250 mg L⁻¹ making it suitable for irrigation.

Sodium

A greater reduction in sodium concentration in treated effluent was observed in 'gravel-sand-charcoal-gravel' among filterbeds and *Typha* among macrophytes (Table 5). The 'gravel-sand-charcoal-gravel' wetland vegetated with *Brachiaria* significantly reduced sodium in the treated effluent. The mean sodium concentration of the PTSE was 10.64 meq L⁻¹ which reduced to 4.57 meq L⁻¹ due to wetland treatment with the magnitude of reduction of 57.0% (Table 3).

Sodium was the dominant cation in both treated and PTSE which was well above the permissible level of 4 meq L⁻¹ for irrigation (Anon. 1985). The reduction in sodium concentration was accredited to the processes of sedimentation, filtration, decomposition, adsorption and plant uptake.

Sodium adsorption ratio (SAR)

Among filterbeds, 'gravel-sand-charcoal-gravel' caused greater reduction in SAR (2.41 mmol^{1/2}L^{-1/2}) while, *Brachiaria*, *Typha* and *Canna* did the same as compared to *Phragmites* (Table 5). The interaction of 'gravel-sand-charcoal-gravel' and *Brachiaria* significantly reduced SAR in TSE (1.84 mmol^{1/2}L^{-1/2}). The reduction in SAR after 120 days was 40.4% as compared to PTSE (Table 3). The reasons for the reduction of SAR in the treated sewage effluent are ingrained in the cause for reduction of sodium.

Bicarbonates

The filterbed, 'gravel-sand-charcoal-gavel' (7.08 meq L⁻¹) was found more efficient in bicarbonate reduction (Table 5). Among macrophytes, *Brachiaria* (9.23 meq L⁻¹) was found less efficient compared to the remaining three; each of them was on par within. The interaction of 'gravel-sand-(charcoal+brick)-gravel' and *Typha* significantly reduced bicarbonates in TSE (6.10 meq L⁻¹).

The comparison of mean data of bicarbonate concentrations of the treated and PTSE revealed a reduction of bicarbonate concentrations to the extent of 48.2 % due to wetland treatment (Table 3). The bicarbonate concentration was higher in both treated and PTSE making it alkaline, more importantly exceeding the recommended level of 1.5 me L⁻¹ (Anon., 1985).

Residual sodium carbonate (RSC)

Among filterbeds, 'gravel-sand-charcoal-gavel' (RSC 1.94 meq L⁻¹) composition was more efficient in lowering RSC (Table 5). The trend between macrophytes remained similar to that observed under bicarbonate concentrations. Except *Brachiaria*, the remaining three macrophytes were equally more effective in reducing RSC. The interaction of 'gravel-sand-charcoal-gavel' and *Canna* recorded significantly lower RSC (1.40 meq L⁻¹). After wetland treatment, the mean RSC was reduced by 50.2% as compared to PTSE (Table 3). The RSC is bound to vary depending on the cationic (calcium + magnesium) and anionic (bicarbonate) concentrations in the raw sewage effluent. The processes like sedimentation, filtration, decomposition, adsorption and plant uptake of these ions are reported as possible reasons for the reduction in RSC. In general, inconsistent results were observed in the reduction of RSC by filterbeds whereas the macrophyte *Canna* consistently proved more efficient in reducing RSC.

Nitrogen forms and total nitrogen

The inorganic nitrogen in wastewater is largely represented by ammoniacal and nitrate nitrogen. However, in wastewaters, the organic nitrogen far exceeds the inorganic forms which is concurrently represented by higher BOD values.

In this study, '*gravel-sand-(charcoal+brick)-gravel*' filterbed registered significantly higher ammoniacal nitrogen ($\text{NH}_4^+ - \text{N}$) and nitrate nitrogen ($\text{NO}_3^- - \text{N}$) as compared to other filterbeds. This also registered significantly lower organic N. This implied that '*gravel-sand-(charcoal+brick)-gravel*' filterbed facilitated higher oxidative conditions resulting in lower levels of organic N and higher levels of inorganic N forms. The same treatment also witnessed greater reduction in BOD. Among macrophytes, *Typha* registered higher $\text{NH}_4^+ - \text{N}$ concentration (13.24 mg L^{-1}) while phragmites higher $\text{NO}_3^- - \text{N}$ (2.40 mg L^{-1}) in treated sewage effluent (Table 5 and 6). The $\text{NH}_4^+ - \text{N}$ concentration in the treated sewage effluent at 120 days remained almost similar to that of PTSE. However, the $\text{NO}_3^- - \text{N}$ concentration was considerably higher by 26.0% in the treated effluent while the organic N was greatly reduced by 92% due to wetland treatment (Table 3). Similar higher reduction in organic N, amounting to 50.6% was witnessed by Zurita *et al.* (2009) for a vertical flow constructed wetland.

Vymazal (2011) reported that a lower hydraulic retention time and a greater oxidation in the rhizosphere of macrophytes created more conducive conditions for faster ammonification process leading to conversion of organic N to $\text{NO}_3^- - \text{N}$. A higher reduction in organic N in treated sewage effluent over PTSE was a clear indication of this fact. The higher extent of oxygenation in the rhizosphere due to complementary effect of filterbed and macrophyte favoured chemolithoautotrophic microbial activity which led to conversion of $\text{NH}_4^+ - \text{N}$ to $\text{NO}_3^- - \text{N}$. The percentage reduction in organic nitrogen in the treated sewage effluent did not exactly match with percentage increase in $\text{NO}_3^- - \text{N}$, obviously due to concomitant uptake by macrophytes (Fig.1).

The total N (TN) concentration registered 35.2% reduction as compared to raw sewage effluent. Comparable results were reported by Kelvin and Tole (2011) who reported a removal efficiency of 41 per cent for TN. These reductions were mediated by nitrifiers such as nitrosomonas, nitropira, nitrosococcus and nitrobacter in both surface and subsurface flow constructed wetlands (Kadlec and Knight. 1996). The reduction in total nitrogen could also be attributed to the process of adsorption of ammoniacal nitrogen on filterbed materials. Among the macrophytes, *Brachiaria* and uptake by macrophytes.

Total phosphorus (TP)

The '*gravel-sand-gravel*' (4.54 mg L^{-1}) filterbed reduced more TP compared to others (Table 5). It might be due to lower effective size of filterbed materials which includes sand as major component. It is evident from Table 1 that sand with minimum size had greater surface area among the filterbed materials accounting for greater adsorption. Similar finding was reported by Seo *et al.* (2005). The most important characteristic of the filterbed material determining its P-removal capacity is its Ca concentration. A considerable Ca concentration in gravel (pH 8.08 indicating the presence of alkaline salts) might have favoured precipitation with P as sparingly soluble calcium phosphates particularly at the slightly alkaline conditions, typical of domestic sewage (Arias *et al.* 2001).

Brachiaria (5.03 mg L^{-1}), *Canna* (5.20 mg L^{-1}) and *Phragmites* (5.13 mg L^{-1}) were on par with each other. The uptake of phosphorus by *Brachiaria* was the highest among the macrophytes (Fig. 1). Whereas, the TP reduction was less by *Typha* (5.54 mg L^{-1}) compared to other macrophytes. The TP in treated sewage effluent across treatments was reduced by 49.3% over the mean TP values of PTSE (Table 3). This reduction is ascribed to the processes like precipitation, plant uptake and adsorption on root surface taking place in the wetland treatment system. The results were in accordance with the findings of Neralla *et al.* (2000), Vera *et al.* (2011) and Arivoli and Mohanraj (2013).

Potassium

The filterbeds viz., '*gravel*' (18.98 mg L^{-1}), '*gravel-sand-brick-gravel*' (17.77 mg L^{-1}) and '*gravel-sand-gravel*' (19.53 mg L^{-1}) reduced more potassium as compared to others (Table 6). The K removal was less in filterbeds involving charcoal indicating that charcoal might have contributed K during wetland treatment. The *Brachiaria* (12.40 mg L^{-1}) was found highly effective in K removal compared to other macrophytes which also witnesses the highest K uptake among macrophytes. The *Brachiaria* planted in '*gravel-sand-gravel*' filterbed significantly reduced potassium (7.15 mg L^{-1}).

Reduction in potassium by 50.7% was observed in treated sewage effluent over PTSE at 120 days (Table 3). The processes like plant uptake and adsorption taking place in the wetland treatment system might be responsible for the reduction in potassium in the treated sewage effluent. The filterbeds viz., '*gravel*' (18.98 mg L^{-1}), '*gravel-sand-brick-gravel*' (17.77 mg L^{-1}) and '*gravel-sand-gravel*' (19.53 mg L^{-1}) reduced more potassium as compared to others (Table 5). The K removal was less in filterbeds involving charcoal indicating that charcoal might have contributed K during wetland treatment. The *Brachiaria* (12.40 mg L^{-1}) was found highly effective in K removal compared to other macrophytes. The *Brachiaria* planted in '*gravel-sand-gravel*' filterbed significantly reduced potassium (7.15 mg L^{-1}).

Reduction in potassium by 50.7% was observed in treated sewage effluent over PTSE at 120 days (Table 3). The processes like plant uptake and adsorption taking place in the wetland treatment system might be responsible for the reduction in potassium in the treated sewage effluent.

Boron

The filterbeds comprising brick or charcoal showed higher removal of boron as compared to only gravel and sand. There was no statistical significance between the macrophytes in respect of boron removal. The reduction in boron concentration in treated sewage effluent was 60.7% over PTSE. The boron concentration of both PTSE and treated effluent were less than 1 mg l^{-1} and was suitable for irrigation. A notable fall in boron concentration of treated sewage effluent was observed, though all the times it was well below the safe limit. Filtration, adsorption and plant uptake might have contributed for the reduction of B in the treated sewage effluent (Vymazal 2011). Though Turker *et al.* (2014) reported that *Phragmites* could be used to decontaminate water containing high concentrations of boron; in our case all macrophytes were equally effective in boron removal.

Conclusion

The inclusion of brick and/or charcoal as filterbed material in addition to sand and gravel has improved the physical filtration capacity of the wetland system. Looking to differential biological filtration ability of macrophytes, inclusion of more than one type of macrophytes would seem more beneficial. In case of specific requirement of remediation of water quality (viz; sodium or boron removal), suitable combination of filterbed and macrophyte may be resolved. The flexibility of selection of filterbed and macrophyte allows the wetland to be adapted to different sites. This flexibility also allows to adapt suitable macrophyte /s in the primary, secondary or tertiary treatment stage.

Declarations

i) **Ethics approval and consent to participate:** Not applicable

ii) **Consent for publication:** Not applicable

iii) **Availability of data and materials:** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

iv) **Competing interests:** The authors declare that they have no competing interests

v) **Funding:** University of Agricultural Sciences, Dharwad, Karnataka, India

vi) **Authors' contributions:** VT conducted the experiment, analyzed the chemical parameters and was a major contributor in writing the manuscript. MH guided VT in the conduct of the experiment, chemical analysis and helped in interpreting the data. MMV designed the experimental set up and helped in conducting the experiment and interpreting the data.

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Tables

Table 1: Physical and chemical properties of filterbed materials used in the study

Filterbed materials	Bulk density (Mg m ⁻³)	Particle density (Mg m ⁻³)	Surface Area (m ² g ⁻¹)	Porosity (%)	pH _{1:2.5}	EC _{1:2.5} (dS m ⁻¹)
Sand	1.59	2.10	2.30 x 10 ⁻³	24.3	7.70	72.2 x 10 ⁻³
Brick	1.60	2.28	0.34 x 10 ⁻³	29.8	8.05	135 x 10 ⁻³
Charcoal	0.38	0.58	0.67 x 10 ⁻³	34.5	7.73	286 x 10 ⁻³
Gravel	1.76	3.14	0.19 x 10 ⁻³	43.9	8.08	46.4 x 10 ⁻³

Table 2: Pore volume and discharge rate of different filterbed columns

Filterbed composition	HRT* (in days)	Pore volume of total length of filterbed (cc)	Discharge rate at the bottom (ml hour ⁻¹)
Gravel	2.5	6920	114.60
Gravel-Sand-Gravel	2.5	5310	88.20
Gravel-Sand- Brick-Gravel	2.5	6110	101.40
Gravel-Sand-Charcoal-Gravel	2.5	6925	115.20
Gravel-Sand-(Brick+Charcoal)-Gravel	2.5	6575	109.20

* Hydraulic retention

Table 3: Mean physico-chemical parameters of untreated sewage effluent during experimentation and treated sewage effluent at 120 days after start

Parameters	Untreated sewage effluent*		Treated sewage effluent (At 120 days)**	Per cent increase (+) / decrease (-) over untreated sewage effluent
	Range	Mean		
pH	8.15-8.47		7.40	-
EC (dS m ⁻¹)	1.23-2.73	2.00	0.99	-50.5
Total dissolved solids (mg L ⁻¹)	886-2909	1376	781	-43.2
Total suspended solids (mg L ⁻¹)	135-402	306	151	-50.7
Total solids (mg L ⁻¹)	1233-3156	1682	933	-44.5
Biological oxygen demand (mg L ⁻¹)	211-305	256	106	-58.6
Chemical oxygen demand (mg L ⁻¹)	416-608	506	226	-55.3
Sodium (meq L ⁻¹)	7.30-13.72	10.64	4.57	-57.0
Sodium adsorption ratio (mmol ^{1/2} L ^{-1/2})	3.87-5.76	4.88	2.91	-40.4
Bicarbonates (meq L ⁻¹)	10.61-20.83	15.2	7.88	-48.2
Residual sodium carbonate (meq L ⁻¹)	3.73-6.97	5.56	2.77	-50.2
Ammoniacal nitrogen (mg L ⁻¹)	9.66-16.56	13.11	13.09	-0.2
Nitrate nitrogen (mg L ⁻¹)	1.33-2.29	1.81	2.28	26.0
Organic nitrogen (mg L ⁻¹)	7.38-12.66	10.02	0.80	-92.0
Total nitrogen (mg L ⁻¹)	18.38-31.50	24.94	16.17	-35.2
Total phosphorus (mg L ⁻¹)	8.08-13.73	10.30	5.22	-49.3
Potassium (mg L ⁻¹)	27.11-63.63	43.03	21.2	-50.7
Boron (mg L ⁻¹)	0.22-0.35	0.28	0.11	-60.7

* From the data of fortnightly observations up to 120 days ; ** Average of treatment combinations

Table 4: Effect of filter beds and macrophytes on pH, electrical conductivity, total dissolved solids, total suspended solids, total solids and biological oxygen demand of treated sewage effluent

Treatments	pH					EC (dS m ⁻¹)					Total dissolved solids (mg L ⁻¹)				
	<i>Typha</i>	<i>Paragrass</i>	<i>Canna</i>	<i>Phragmites</i>	Mean	<i>Typha</i>	<i>Paragrass</i>	<i>Canna</i>	<i>Phragmites</i>	Mean	<i>Typha</i>	<i>Paragrass</i>	<i>Canna</i>	<i>Phragmites</i>	Mean
Macrophytes à															
Filterbeds à															
Gravel	7.71	7.46	7.52	7.38	7.52 ^a	1.07	1.06	1.08	1.06	1.07 ^b	699	673	767	829	742 ^c
Gravel -Sand-Gravel	7.22	7.37	7.48	7.35	7.36 ^c	1.09	1.10	1.09	1.05	1.09 ^a	801	707	793	851	788 ^b
Gravel-Sand-Brick-Gravel	7.42	7.56	7.47	7.39	7.46 ^b	1.00	0.98	1.06	1.07	1.03 ^c	741	823	835	899	825 ^a
Gravel-Sand-Charcoal-Gravel	7.43	7.59	7.59	7.28	7.47 ^b	1.08	1.06	0.80	0.67	0.90 ^d	847	729	683	831	773 ^b
Gravel-Sand-Charcoal+Brick)-Gravel	7.13	7.11	7.27	7.23	7.18 ^d	0.87	1.06	0.67	0.89	0.87 ^e	845	705	815	755	780 ^b
Mean	7.38 ^c	7.42 ^b	7.46 ^a	7.33 ^d		1.02 ^b	1.05 ^a	0.94 ^c	0.95 ^c		787 ^b	727 ^c	779 ^b	833 ^a	
	S. Em. ±		C. D. (P=0.05)			S. Em. ±		C. D. (P=0.05)			S. Em. ±		C. D. (P=0.05)		
Filterbeds	0.005		0.015			0.002		0.005			4.52		12.98		
Macrophytes	0.005		0.013			0.002		0.005			4.05		12.62		
Filterbeds × Macrophytes	0.010		0.030			0.004		0.010			9.05		25.97		

	Total suspended solids (mg L ⁻¹)					Total solids (mg L ⁻¹)					Biological oxygen demand (mg L ⁻¹)				
Gravel	117	133	161	359	193 ^a	816	806	928	1188	935 ^{bc}	116	108	112	118	113 ^a
Gravel -Sand-Gravel	127	137	341	107	178 ^b	928	844	1134	958	966 ^a	106	100	105	116	107 ^b
Gravel-Sand-Brick-Gravel	133	147	147	55	121 ^e	874	970	982	954	945 ^b	114	117	116	110	114 ^a
Gravel-Sand-Charcoal-Gravel	141	97	137	137	128 ^d	988	826	820	968	901 ^d	108	106	111	103	107 ^b
Gravel-Sand-Charcoal+Brick)-Gravel	227	39	119	171	139 ^c	1072	744	934	926	919 ^{cd}	89.3	99.3	88.3	91.3	92.1 ^c
Mean	149 ^c	111 ^d	181 ^a	166 ^b		936 ^c	838 ^d	960 ^b	999 ^a		106 ^{ab}	106 ^b	106 ^{ab}	107 ^a	
	S. Em. ±		C. D. (P=0.05)			S. Em. ±		C. D. (P=0.05)			S. Em. ±		C. D. (P=0.05)		
Filterbeds	0.98		2.81			5.42		15.56			0.36		1.02		
Macrophytes	0.87		2.51			4.85		13.91			0.32		0.92		
Filterbeds × Macrophytes	1.96		5.62			10.85		31.11			0.71		2.05		

NS- Non significant

ble 5: Effect of filterbeds and macrophytes on chemical oxygen demand, sodium, sodium adsorption ratio, bicarbonate, residual sodium carbonate and moniacal nitrogen of treated sewage effluent

Treatments	Chemical oxygen demand (mg L ⁻¹)					Sodium (meq L ⁻¹)					Sodium adsorption ratio (mmol ^{1/2} L ^{-1/2})				
	<i>Typha</i>	<i>Paragrass</i>	<i>Canna</i>	<i>Phragmites</i>	Mean	<i>Typha</i>	<i>Paragrass</i>	<i>Canna</i>	<i>Phragmites</i>	Mean	<i>Typha</i>	<i>Paragrass</i>	<i>Canna</i>	<i>Phragmites</i>	Mean
Macrophytes à Filterbeds à															
Gravel	239	236	235	225	233 ^{ab}	4.81	4.68	5.22	5.30	5.00 ^a	2.95	2.89	3.62	3.27	3.19
Gravel -Sand- Gravel	237	233	231	240	235 ^a	4.54	5.09	4.36	4.64	4.66 ^b	3.00	2.98	2.70	2.93	2.93
Gravel-Sand-Brick- Gravel	237	228	229	236	232 ^b	4.72	4.74	4.24	4.63	4.58 ^b	3.07	2.76	2.64	2.85	2.83
Gravel-Sand- Charcoal-Gravel	225	218	221	224	222 ^c	3.14	3.09	4.38	4.74	3.84 ^c	1.96	1.84	2.63	3.22	2.41
Gravel-Sand- (Charcoal+Brick)- Gravel	217	213	208	211	212 ^d	4.47	5.30	4.62	4.77	4.79 ^{ab}	3.39	3.29	2.97	3.32	3.24
Mean	231 ^a	225 ^{bc}	224 ^c	227 ^b		4.34 ^b	4.58 ^{ab}	4.57 ^b	4.82 ^a		2.87 ^b	2.75 ^b	2.91 ^b	3.12 ^a	
	S. Em. ±		C. D. (P=0.05)			S. Em. ±		C. D. (P=0.05)			S. Em. ±		C. D. (P=0.05)		
Filterbeds	0.66		1.88			0.07		0.20			0.05		0.14		
Macrophytes	0.59		1.68			0.06		0.14			0.05		0.13		
Filterbeds × Macrophytes	1.31		3.77			0.14		0.41			0.10		0.28		

Treatments	Bicarbonate (meq L ⁻¹)					Residual sodium carbonate (meq L ⁻¹)					Ammoniacal nitrogen (mg L ⁻¹)				
	<i>Typha</i>	<i>Paragrass</i>	<i>Canna</i>	<i>Phragmites</i>	Mean	<i>Typha</i>	<i>Paragrass</i>	<i>Canna</i>	<i>Phragmites</i>	Mean	<i>Typha</i>	<i>Paragrass</i>	<i>Canna</i>	<i>Phragmites</i>	Mean
Gravel	8.53	10.10	7.80	9.30	8.93 ^a	3.27	4.50	3.10	3.37	3.56 ^a	13.11	12.09	13.70	13.11	13.01
Gravel -Sand- Gravel	7.60	10.70	8.47	8.07	8.71 ^a	2.77	4.87	3.43	2.93	3.50 ^a	13.65	13.58	13.88	12.46	13.39
Gravel-Sand-Brick- Gravel	7.87	8.27	6.40	7.17	7.43 ^b	2.97	2.37	1.47	1.70	2.13 ^c	12.41	11.62	9.99	11.34	11.34
Gravel-Sand- Charcoal-Gravel	6.60	8.60	6.73	6.40	7.08 ^b	1.47	2.73	1.40	2.17	1.94 ^c	12.55	13.00	13.79	14.12	13.34
Gravel-Sand- (Charcoal+Brick)- Gravel	6.10	8.47	7.80	6.70	7.27 ^b	2.23	3.63	2.63	2.53	2.76 ^b	14.49	14.42	14.30	14.26	14.37
Mean	7.34 ^b	9.23 ^a	7.44 ^b	7.53 ^b		2.54 ^b	3.62 ^a	2.40 ^b	2.54 ^b		13.24 ^a	12.94 ^c	13.13 ^{ab}	13.06 ^{bc}	
	S. Em. ±		C. D. (P=0.05)			S. Em. ±		C. D. (P=0.05)			S. Em. ±		C. D. (P=0.05)		
Filterbeds	0.13		0.35			0.12		0.35			0.05		0.14		
Macrophytes	0.11		0.33			0.11		0.32			0.04		0.12		
Filterbeds × Macrophytes	0.26		0.76			0.24		0.70			0.10		0.28		

NS- Non significant

ble 6: Effect of filterbeds and macrophytes on nitrate nitrogen, organic nitrogen, total nitrogen, total phosphorus, potassium and boron treated sewage effluent

Treatments	Nitrate nitrogen (mg L ⁻¹)					Organic nitrogen (mg L ⁻¹)					Total nitrogen (mg L ⁻¹)				
	<i>Typha</i>	<i>Paragrass</i>	<i>Canna</i>	<i>Phragmites</i>	Mean	<i>Typha</i>	<i>Paragrass</i>	<i>Canna</i>	<i>Phragmites</i>	Mean	<i>Typha</i>	<i>Paragrass</i>	<i>Canna</i>	<i>Phragmites</i>	Mean
Macrophytes à															
Filterbeds à															
Gravel	2.12	1.97	1.85	1.91	1.96 ^e	0.74	1.25	0.43	0.93	0.84 ^b	15.97	15.31	15.97	15.95	15.80 ^c
Gravel -Sand-Gravel	1.78	2.05	2.15	2.26	2.06 ^d	0.82	0.93	1.12	0.82	0.92 ^b	16.25	16.57	17.15	15.54	16.38 ^b
Gravel-Sand-Brick-Gravel	2.09	2.13	2.23	2.23	2.17 ^c	1.10	1.47	1.82	1.12	1.38 ^a	15.60	15.22	14.03	14.69	14.89 ^d
Gravel-Sand-Charcoal-Gravel	2.30	2.55	2.18	2.80	2.46 ^b	1.14	0.63	0.47	0.30	0.64 ^c	16.00	16.18	16.44	17.22	16.46 ^b
Gravel-Sand-Charcoal+Brick)-Gravel	2.76	2.72	2.77	2.79	2.76 ^a	0.20	0.14	0.37	0.19	0.22 ^d	17.44	17.28	17.45	17.23	17.35 ^a
Mean	2.21 ^c	2.29 ^b	2.24 ^c	2.40 ^a		0.80 ^a	0.89 ^a	0.84 ^a	0.67 ^b		16.25	16.11	16.21	16.13	
	S. Em. ±		C. D. (P=0.05)			S. Em. ±		C. D. (P=0.05)			S. Em. ±		C. D. (P=0.05)		
Filterbeds	0.01		0.03			0.03		0.07			0.05		0.14		
Macrophytes	0.01		0.03			0.02		0.06			0.05		NS		
Filterbeds × Macrophytes	0.02		0.06			0.06		0.15			0.10		0.29		
	Total phosphorus (mg L ⁻¹)					Potassium (mg L ⁻¹)					Boron (mg L ⁻¹)				
Gravel	7.38	6.46	7.29	6.67	6.95 ^a	13.90	18.37	20.17	23.47	18.98 ^b	0.12	0.11	0.13	0.11	0.12 ^a
Gravel -Sand-Gravel	4.67	4.49	4.51	4.51	4.54 ^c	27.02	7.15	17.34	26.63	19.53 ^b	0.11	0.11	0.11	0.13	0.11 ^b
Gravel-Sand-Brick-Gravel	5.65	4.52	4.59	5.13	4.97 ^b	28.40	8.60	16.28	17.79	17.77 ^b	0.10	0.10	0.11	0.11	0.10 ^c
Gravel-Sand-Charcoal-Gravel	5.12	4.93	4.68	4.63	4.84 ^{bc}	32.75	9.28	22.25	31.00	23.82 ^a	0.10	0.11	0.11	0.11	0.10 ^c
Gravel-Sand-Charcoal+Brick)-Gravel	4.85	4.75	4.91	4.73	4.81 ^{bc}	33.26	18.59	21.50	30.31	25.92 ^a	0.11	0.11	0.09	0.11	0.10 ^c
Mean	5.54 ^a	5.03 ^b	5.20 ^b	5.13 ^b		27.07 ^a	12.40 ^c	19.51 ^b	25.84 ^a		0.11	0.11	0.11	0.11	
	S. Em. ±		C. D. (P=0.05)			S. Em. ±		C. D. (P=0.05)			S. Em. ±		C. D. (P=0.05)		
Filterbeds	0.09		0.25			0.84		2.41			0.001		0.002		
Macrophytes	0.08		0.22			0.75		2.15			0.001		NS		
Filterbeds × Macrophytes	0.18		0.50			1.68		4.81			0.003		0.007		

NS- Non significant

Figures

Figure 1

Schematic diagram of composition of filterbeds(not to scale)

Figure 2

Figure 3

Plate 1. Experimental set-up