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Performance of Filter Beds and Macrophytes in a Vertically Constructed Wetland for Treating Domestic Sewage Effluents

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

An experiment with different filter beds and macrophytes was carried out to study their phytoremediation capacity on the efficiency of domestic wastewater treatment through constructed wetland (CW) from November to March 2017-18 at the University of Agricultural Sciences, Dharwad campus, Karnataka. Twenty treatment combinations involving five types of filter beds (FB-1: *gravel*, FB-2: *gravel-sand-gravel*, FB-3: *gavel-sand-brick-gravel*, FB-4: *gravel-sand-charcoal-gravel* and

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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 sp*.) were evaluated for treating domestic waste water. 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 percent due to wetland treatment. The system enhanced the mineralization of organic nitrogen to ammoniacal nitrogen (NH_4^+-N) and nitrate-nitrogen (NO_3-N) fractions. Among filter beds, Type-5 caused a 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 filter bed 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 the main, secondary, or tertiary treatment stage.

Keywords: Sewage effluent; constructed wetland; filter beds; macrophytes; water quality parameters.

1. INTRODUCTION

Water, food, and energy securities are emerging as increasingly important and indispensable issues for India and the world. Water is vital yet, constrained resource in most developing nations. The average availability of potable water is dwindling steadily, and India may become a water-scarce country by 2025. Thus, recycling, and reusing water need greater attention. About 38,354 million liters per day (MLD) of sewage water are generated in major cities of India. However, the total sewage treatment capacity in these cities is only 22,963 MLD. 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. 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 ecosystems. 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 percent of total freshwater for irrigation. India’s agriculture sector, which is the backbone of the Indian economy, right now utilizes around 90 percent 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, the fast depletion of groundwater reserves coupled with severe water pollution has placed India in a 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 has made the problem worse and difficult to manage.

Sewage irrigation is an age-old farming practice, and the 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 an expansive range of taints *viz*., bio-degradable organic compounds, toxic metals, suspended solids, micro-pathogens, and parasites [1,2] which restrict its direct application to the field.

In developing nations like India, the issues related to 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 the degradation of our valuable natural resources [3]; (Ji et al., 2022). 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.

Natural processes have always cleansed water as it flows through rivers, lakes, streams, and wetlands in nature. In developing countries, natural treatment systems are considered more suitable and 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 [4]. Wetlands with hydrophytes are one of the many types of natural systems that can be used for the treatment of municipal wastewater.

An enormous quantity of sewage water is generated in major cities of India. Only a portion of this generated sewage water is treated with conventional sewage treatment plants, which are very expensive, need energy, and require regular maintenance. On the other hand, farmers are directly using this sewage water without treatment for crop production. This causes severe health hazards to human beings and also soils will be degraded with time. To overcome the problem of these environmental challenges and re-use of sewage water for crop production, the experiment was carried out at the Agricultural University Campus, Dharwad to study the performance of different filter beds and macrophytes in a vertically constructed wetland for treating domestic sewage effluent.

The major nutrient removal mechanisms associated with constructed wetland systems include biodegradation, precipitation, and filtration [5,6]. The choice of materials for filter beds and their vertical arrangement, thickness/depth-wise, should aim at maximizing the efficiency of these foresaid processes and minimizing the treatment cost. Hubli-Dharwad twin city produces 60 million liters of waste water per day, none is treated. The waste water flows into natural courses, and along their routes farmers exploit these resource for irrigation. Waste water irrigation cautioned that direct and indiscriminate use may create soil and human health problems. Keeping these in mind, the present study (column study) was carried out to know the effect of different filter beds and macrophytes on the quality of treated domestic sewage effluent and to estimate the nutrient removal capacity by locally available materials such as gravel, sand, charcoal, and brick materials.

2. 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 filter beds (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 sp*.) 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 (Fig. 1). The bottom end of the pipe was closed with an 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*' filter bed where the entire column was filled with gravel) was filled with sole or combinations of different filter bed materials. In the '*Gravel-Sand-Gravel'* filter bed, the middle 30 cm was filled with sand (0.02- 2.0 mm). In the '*Gavel-Sand-Brick-Gravel'* filter bed, 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 the '*Gravel-Sand-Charcoal-Gravel'* filter bed, the top 15 cm was filled with sand and the lower 15 cm with charcoal (~ 20 mm). In the '*Gravel-Sand-(Charcoal+Brick)-Gravel'* filter bed, the top 15 cm was filled with sand and the lower 15 cm with an equal (50:50 by w/w) mixture of charcoal and brick material (Fig. 1). The physical properties of the filter bed materials are given in Table 1. The hydraulic retention time was worked out using the formula given below:

$$\text{Hydraulic retention time (HRT, in days)} = \frac{\text{Total storage (cc)}}{\text{Influent flow rate (cc/day)}}$$

The total storage (porosity volume, cc) was calculated from the porosities of the proportionate contents of filter bed materials filled in each column, which differed among filter bed treatments (Table 2 and Fig. 2). The hydraulic retention time was set uniformly at 2.5 days by regulating the 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 the University campus, Dharwad, and reared in plastic trays with minimum soil. Young plants of macrophytes raised using a sand medium were transplanted in the top layer of gravel in each column after washing off the sand and adhering to roots. The columns were irrigated with primary treated sewage effluent (PTSE). Every day, the treated water collected in the drain-can was decanted and once in 15 days, the treated water was collected and stored in a refrigerator for physicochemical analysis.

The PTSE from the sedimentation tank in the flow stream on 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 analyzed120 days from the start of the study. The water quality parameters were analyzed by following standard methods: pH (pH meter), EC (Conductivity meter) [7]; total phosphorus (Ascorbic acid using spectrophotometer) and BOD (Incubation at 20°C for five days) [8]; COD (Open reflex method), sodium, ammoniacal nitrogen (Distillation), nitrate-nitrogen (Distillation), total nitrogen (Digestion with concentrated H2SO4 followed by distillation), SAR, RSC, and bicarbonates (Titration against 0.05 N sulphuric acid) [9]; total dissolved solids (Gravimetric method), total suspended solids (Filtration method), total solids (Gravimetric method), and boron (Azomethine-H method) [10].

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. In the end, the total dry shoot biomass of each macrophyte for 120 days was obtained by 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 [11]. The N, P, and K uptake by the plant was worked out using the following equation:

$$\text{NPK uptake (g column}^{-1}\text{)} = \frac{\text{NPK content (\%)} \times \text{Dry matter yield of the plant (g column}^{-1}\text{)}}{100}$$

2.1 Statistical Analyses

The statistical interpretation of the experimental data was done by following Fischer’s variance analysis technique as given by Gomez and Gomez [12]. The experimental data were analyzed as per Factorial CRD to compare the filter beds, macrophytes and the interaction between the two. The results were computed at 5 % (P = 0.05) level of significance. Critical differences (CD) were worked out whenever the ‘F’ test was significant and treatment means were compared by applying Duncan’s multiple range test (DMRT).

3. RESULTS AND DISCUSSION

The average characteristics of the primary treated sewage effluent (PTSE) are given in Table 3. The pH was moderately alkaline (8.35) with a considerable amount of salts (2.0 dS m^{-1}). The effluent had total dissolved and suspended solids of 1376 and 306 mg L^{-1}, respectively. The BOD (256 mgL^{-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 filter beds and macrophytes.

Table 1. Physical and chemical properties of filter bed materials used in the study

Filter bed 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 filter bed columns

Filter bed composition	**HRT* (in days)**	**Pore volume of total length of filter bed (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 time*

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})**				
Macrophytes → Filter beds ↓	***Typha***	***Paragrass***	***Canna***	***Phragmites***	**Mean**	***Typha***	***Paragrass***	***Canna***	***Phragmites***	**Mean**	***Typha***	***Paragrass***	***Canna***	***Phragmites***	**Mean**
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}
Gavel-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)		
Filter beds	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		
Filter beds × 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}
Gavel-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)**		
Filter beds	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		
Filter beds × Macrophytes	1.96		5.62			10.85		31.11			0.71		2.05		

NS- Non significant

Table 5. Effect of filter beds and macrophytes on chemical oxygen demand, sodium, sodium adsorption ratio, bicarbonate, residual sodium carbonate and ammoniacal nitrogen of treated sewage effluent

Treatments	**Chemical oxygen demand (mg L^{-1})**					**Sodium (meq L^{-1})**					**Sodium adsorption ratio (mmol$^{1/2}$ L$^{-1/2}$)**				
Macrophytes → Filter beds ↓	***Typha***	***Paragrass***	***Canna***	***Phragmites***	**Mean**	***Typha***	***Paragrass***	***Canna***	***Phragmites***	**Mean**	***Typha***	***Paragrass***	***Canna***	***Phragmites***	**Mean**
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^{a}
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	2.91^{b}
Gavel-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^{b}
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^{c}
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^{a}
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)		
Filter beds	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		
Filter beds × Macrophytes	1.31		3.77			0.14		0.41			0.10		0.28		
	Bicarbonate (meq L^{-1})					**Residual sodium carbonate (meq L^{-1})**					**Ammoniacal nitrogen (mg L^{-1})**				
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	13.00^{c}
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^{b}
Gavel-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^{d}
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	13.36^{b}
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^{a}
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)**		
Filter beds	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		
Filter beds × Macrophytes	0.26		0.76			0.24		0.70			0.10		0.28		

NS- Non significant

Table 6. Effect of filter beds and macrophytes on nitrate nitrogen, organic nitrogen, total nitrogen, total phosphorus, potassium and boron of treated sewage effluent

Treatments	**Nitrate nitrogen (mg L^{-1})**					**Organic nitrogen (mg L^{-1})**					**Total nitrogen (mg L^{-1})**				
Macrophytes → **Filter beds ↓**	***Typha***	***Paragrass***	***Canna***	***Phragmites***	**Mean**	***Typha***	***Paragrass***	***Canna***	***Phragmites***	**Mean**	***Typha***	***Paragrass***	***Canna***	***Phragmites***	**Mean**
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}
Gavel-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)		
Filter beds	0.01		0.03			0.03		0.07			0.05		0.14		
Macrophytes	0.01		0.03			0.02		0.06			0.05		NS		
Filter beds × 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}
Gavel-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)**		
Filter beds	0.09		0.25			0.84		2.41			0.001		0.002		
Macrophytes	0.08		0.22			0.75		2.15			0.001		NS		
Filter beds × Macrophytes	0.18		0.50			1.68		4.81			0.003		0.007		

NS- Non significant

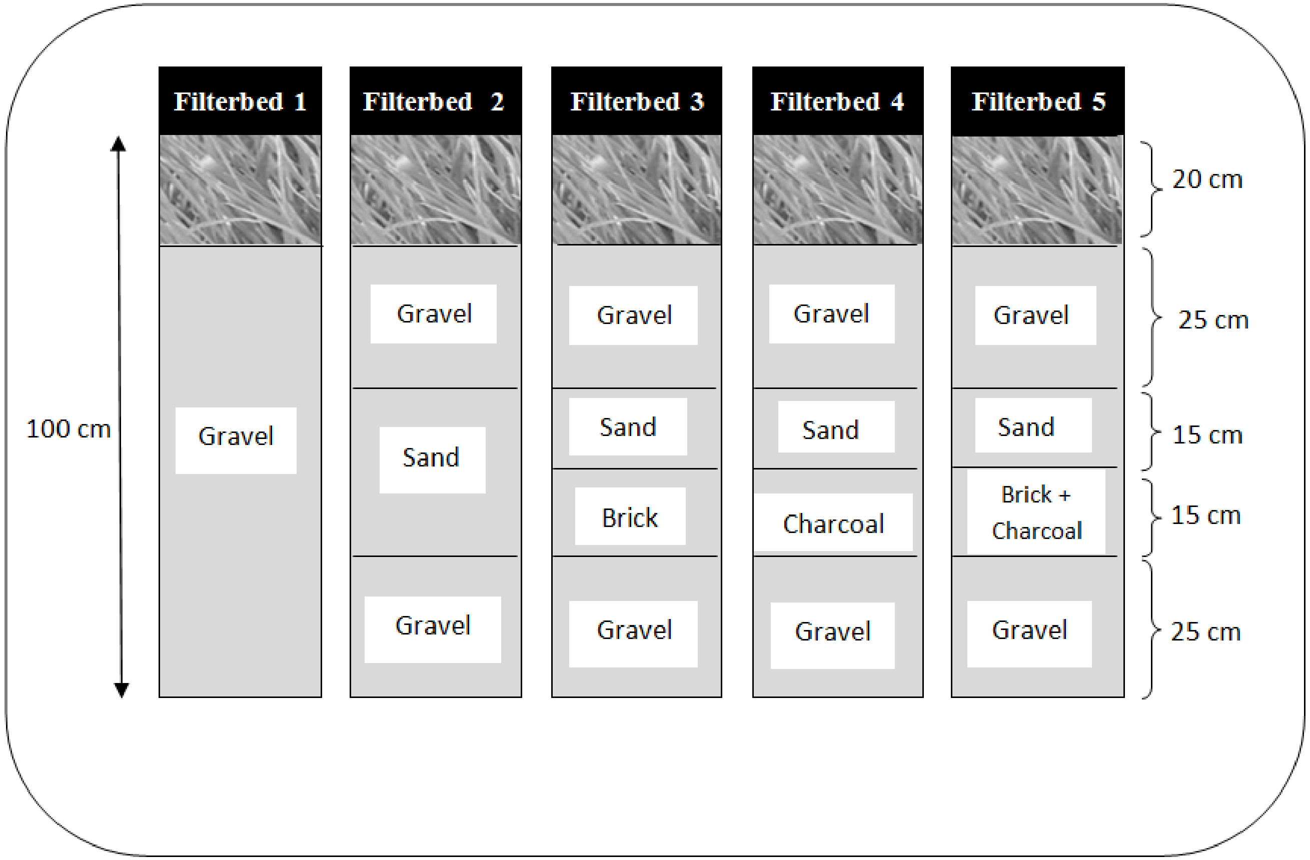


Fig. 1. Schematic diagram of composition of filterbeds (not to scale)

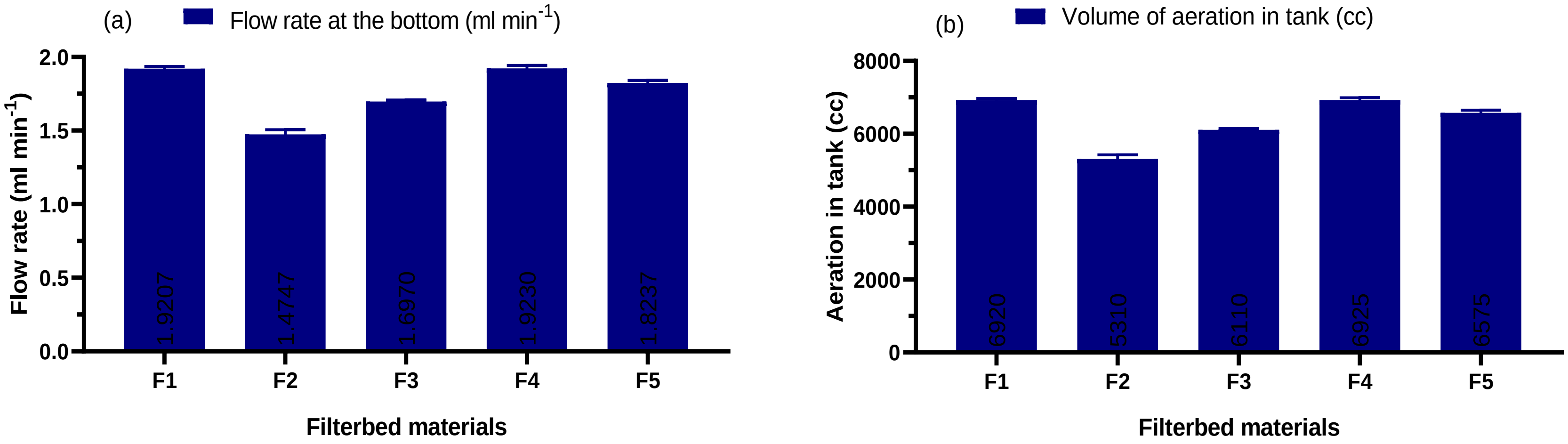
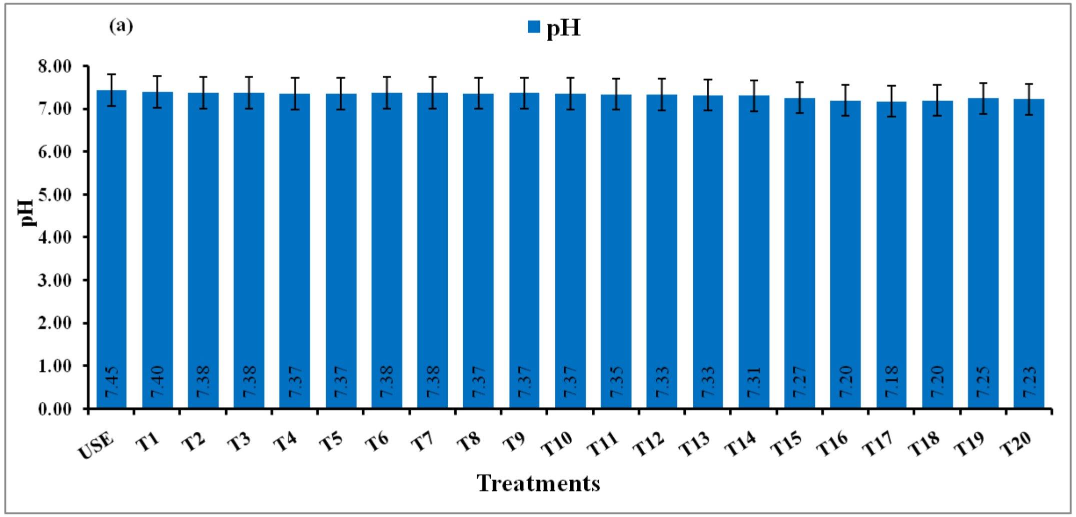
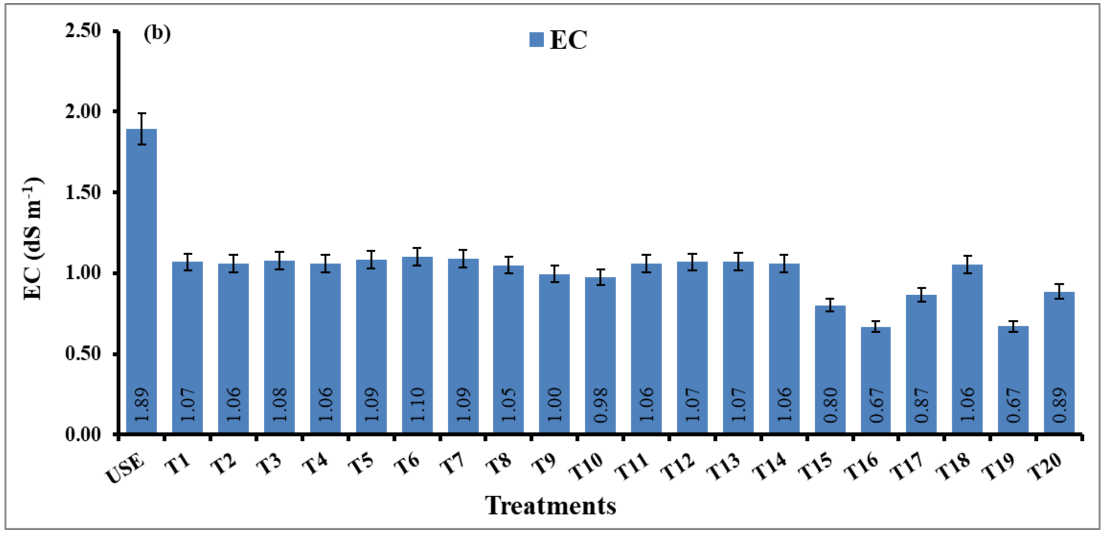
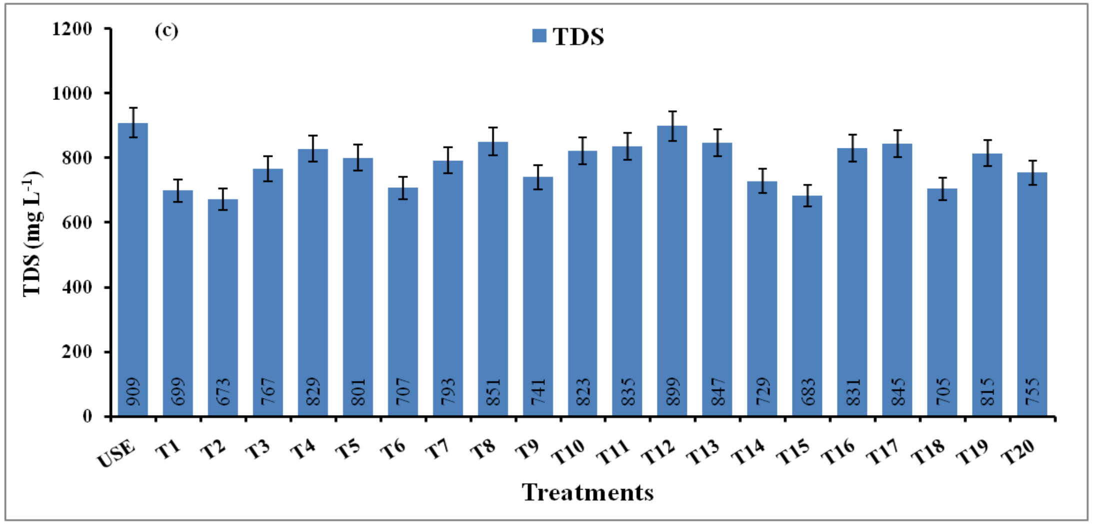
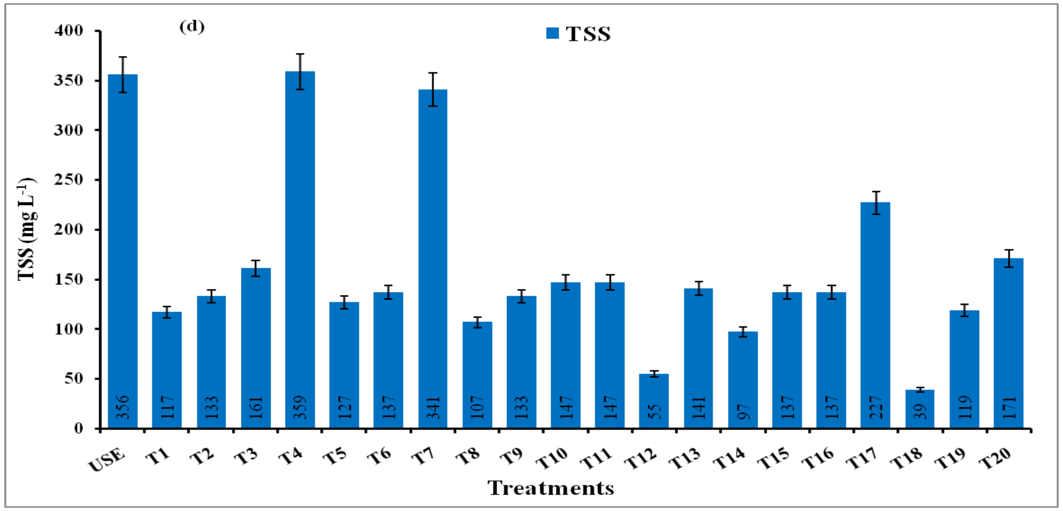


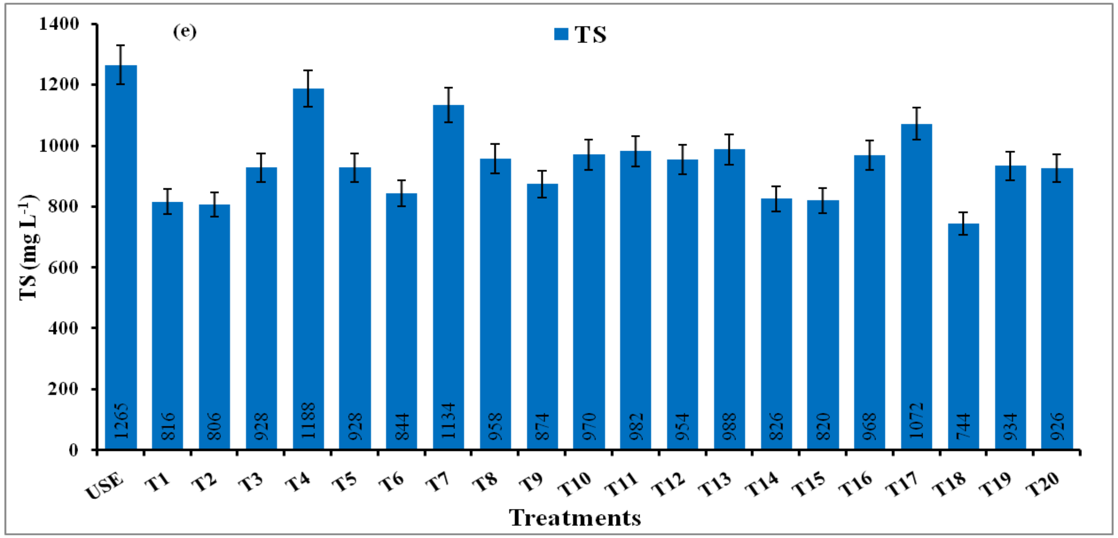
Fig. 2. (a) Flow rate at the bottom, and (b) volume of aeration affected by different filter beds. HRT for 2.5 days was fixed for all the treatments. Based on volume of aeration in tank discharge rate was calculated and outflow rate for each column was fixed; HRT= volume of aeration in tank (cc)/ flowrate at the bottom (cc/Min)

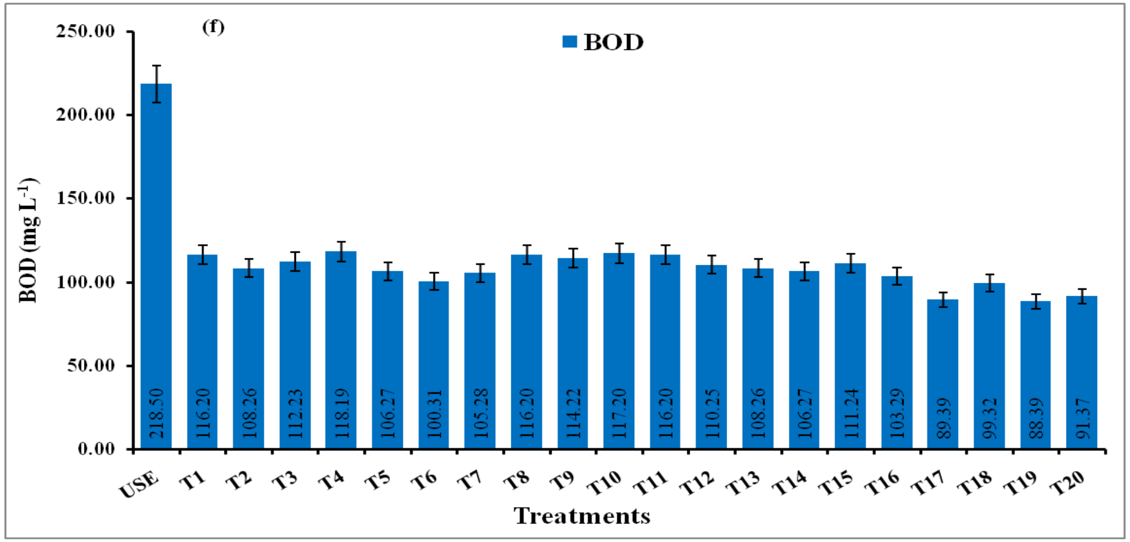

(a)
■ pH
pH
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
7.45
7.40
7.38
7.38
7.37
7.37
7.38
7.38
7.37
7.37
7.37
7.35
7.33
7.33
7.31
7.27
7.20
7.18
7.20
7.25
7.23
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments

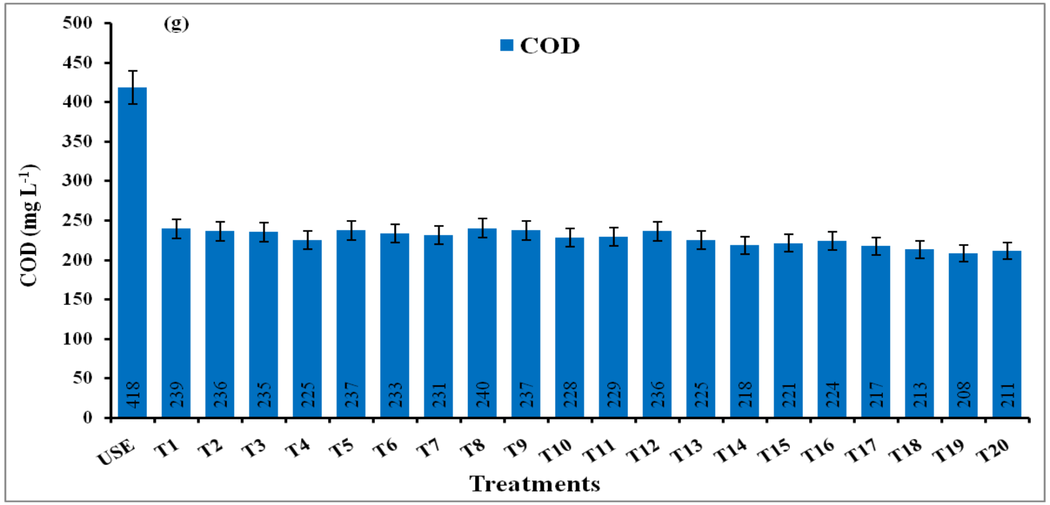

(b)
■ EC
EC (dS m-1)
2.50
2.00
1.50
1.00
0.50
0.00
1.89
1.07
1.06
1.08
1.06
1.09
1.10
1.09
1.05
1.00
0.98
1.06
1.07
1.07
1.06
0.80
0.67
0.87
1.06
0.67
0.89
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments

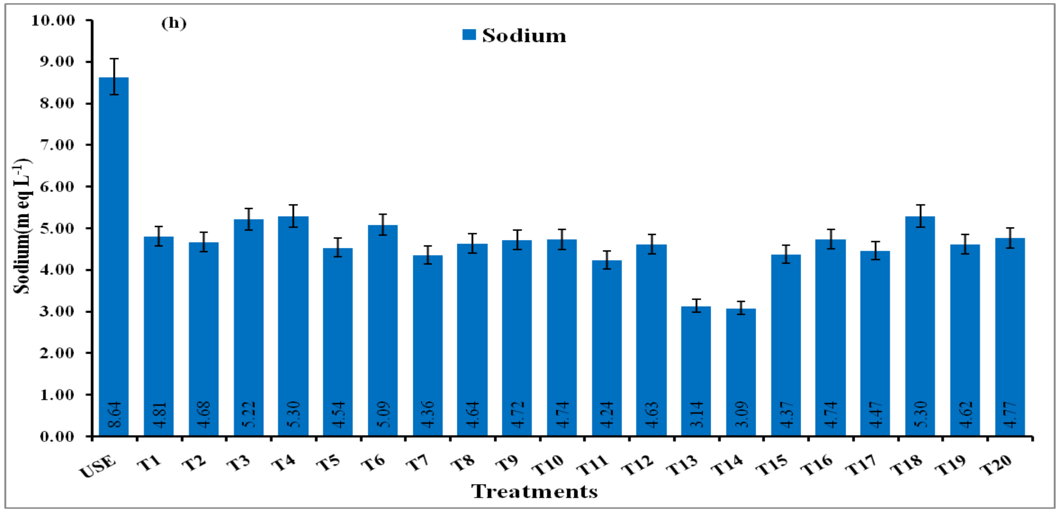

(c)
■ TDS
TDS (mg L-1)
1200
1000
800
600
400
200
0
909
699
673
767
829
801
707
793
851
741
823
835
899
847
729
683
831
845
705
815
755
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments

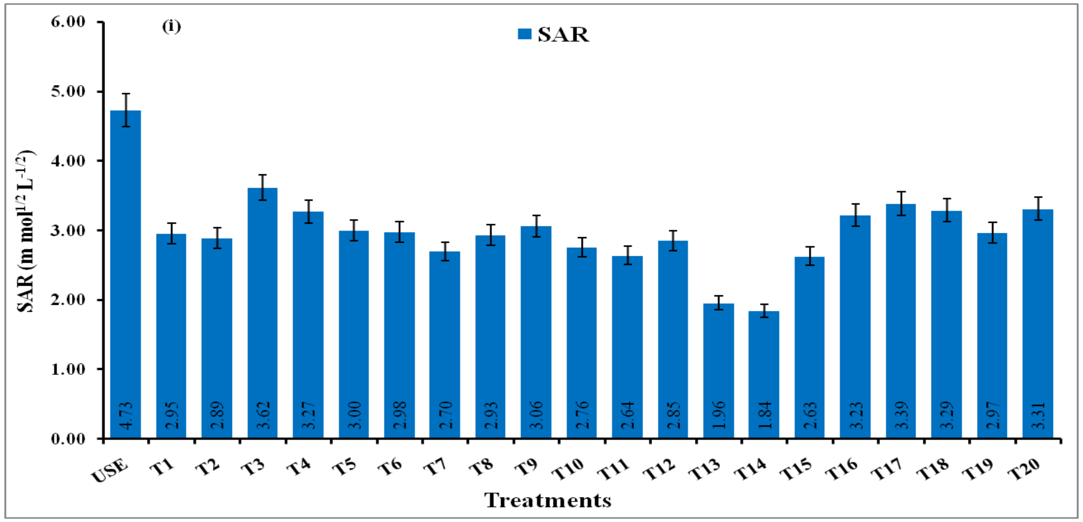

(d)
■ TSS
TSS (mg L-1)
400
350
300
250
200
150
100
50
0
356
117
133
161
359
127
137
341
107
133
147
147
55
141
97
137
137
227
39
119
171
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments

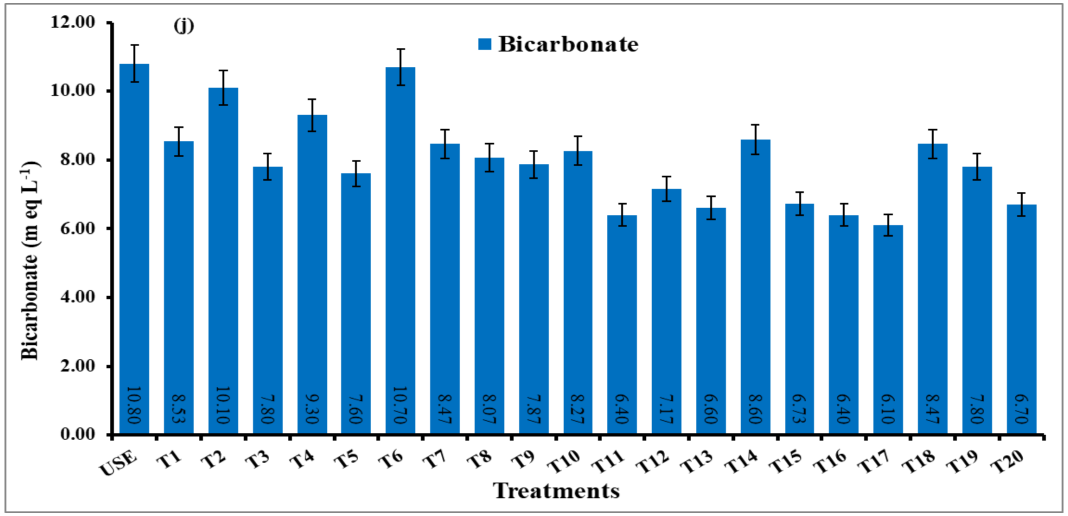

(e)
■ TS
TS (mg L-1)
1400
1200
1000
800
600
400
200
0
1265
816
806
928
1188
928
844
1134
958
874
970
982
954
988
826
820
968
1072
744
934
926
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments

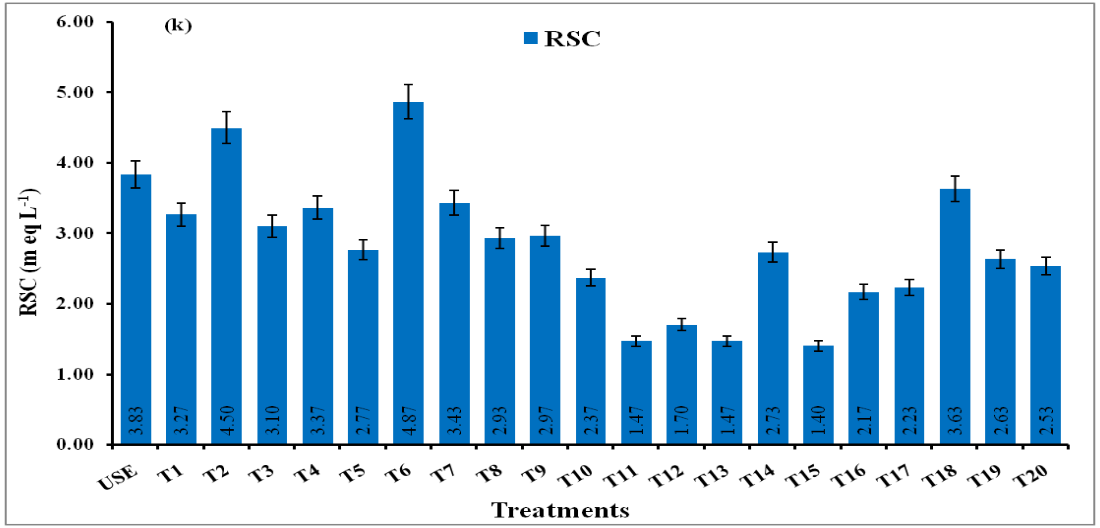

(f)
■ BOD
BOD (mg L-1)
250.00
200.00
150.00
100.00
50.00
0.00
218.50
116.20
108.26
112.23
118.19
106.27
100.31
105.28
116.20
114.22
117.20
116.20
110.25
108.26
106.27
111.24
103.29
89.39
99.32
88.39
91.37
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments

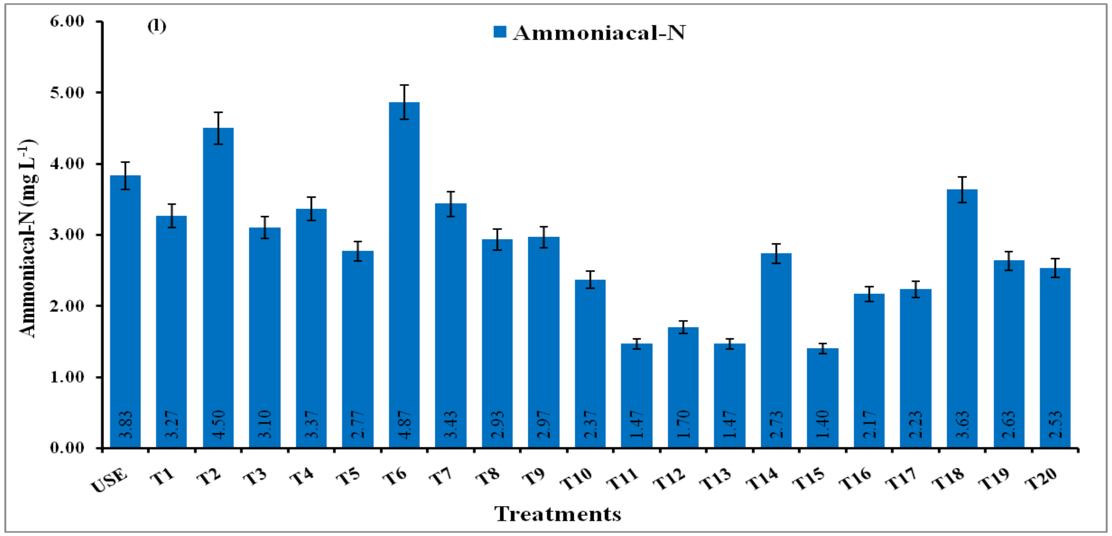

(g)
COD
COD (mg L^{-1})
500
450
400
350
300
250
200
150
100
50
0
418
239
236
235
225
237
233
231
240
237
228
229
236
225
218
221
224
217
213
208
211
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments

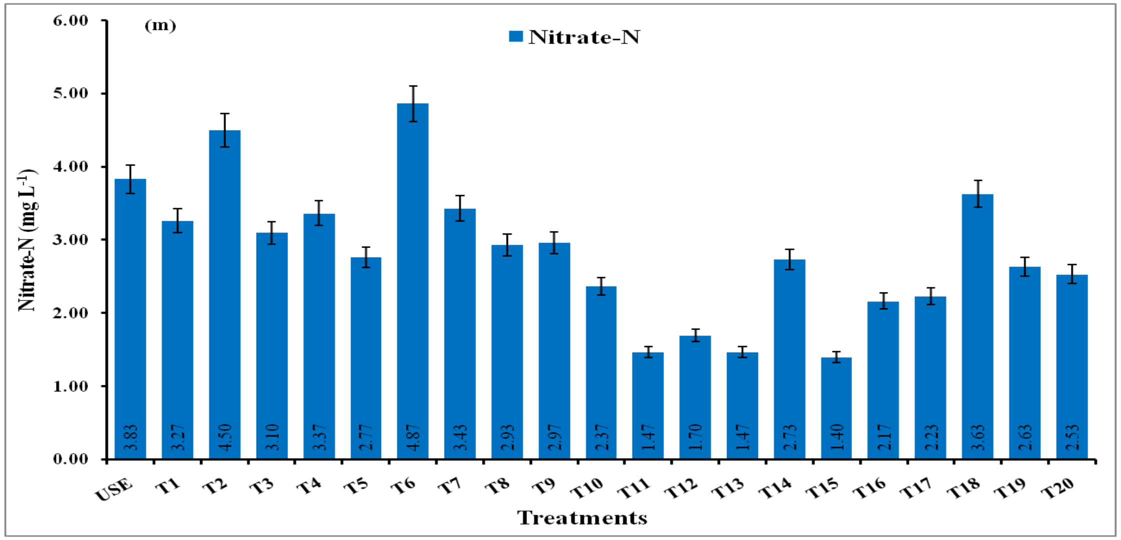

(h)
Sodium
Sodium(m eq L^{-1})
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
8.64
4.81
4.68
5.22
5.30
4.54
5.09
4.36
4.64
4.72
4.74
4.24
4.63
3.14
3.09
4.37
4.74
4.47
5.30
4.62
4.77
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments

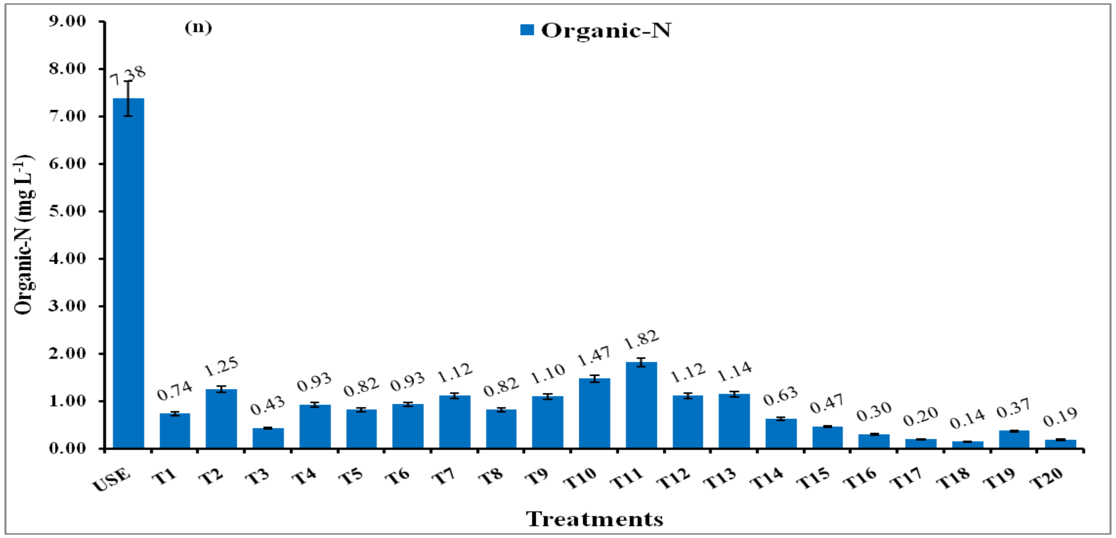

(i)
SAR
SAR (m mol1/2 L-1/2)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
4.73
2.95
2.89
3.62
3.27
3.00
2.98
2.70
2.93
3.06
2.76
2.64
2.85
1.96
1.84
2.63
3.23
3.39
3.29
2.97
3.31
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments

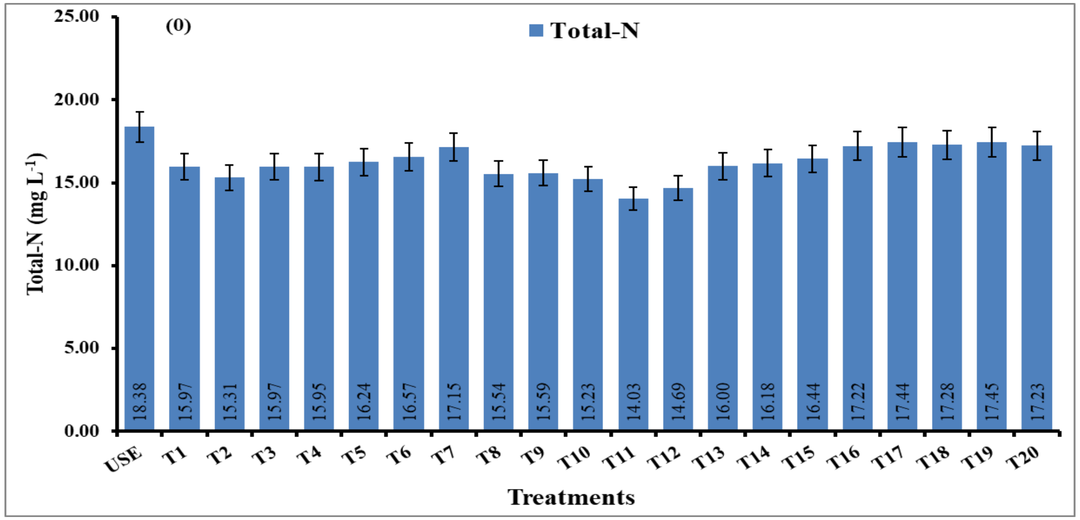

(j)
Bicarbonate
Bicarbonate (m eq L-1)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
10.80
8.53
10.10
7.80
9.30
7.60
10.70
8.47
8.07
7.87
8.27
6.40
7.17
6.60
8.60
6.73
6.40
6.10
8.47
7.80
6.70
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments

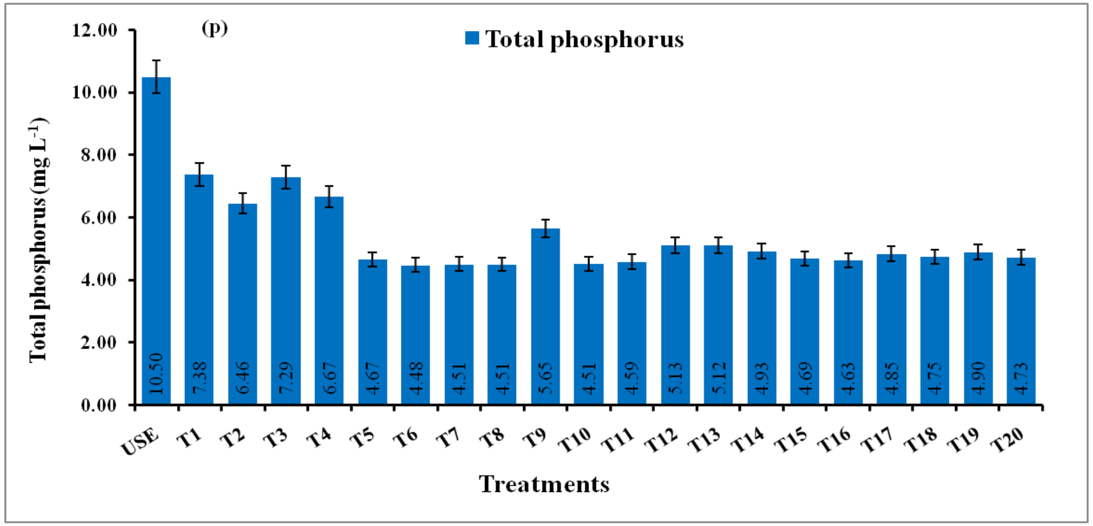

(k)
RSC
RSC (m eq L^{-1})
6.00
5.00
4.00
3.00
2.00
1.00
0.00
3.83
3.27
4.50
3.10
3.37
2.77
4.87
3.43
2.93
2.97
2.37
1.47
1.70
1.47
2.73
1.40
2.17
2.23
3.63
2.63
2.53
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments

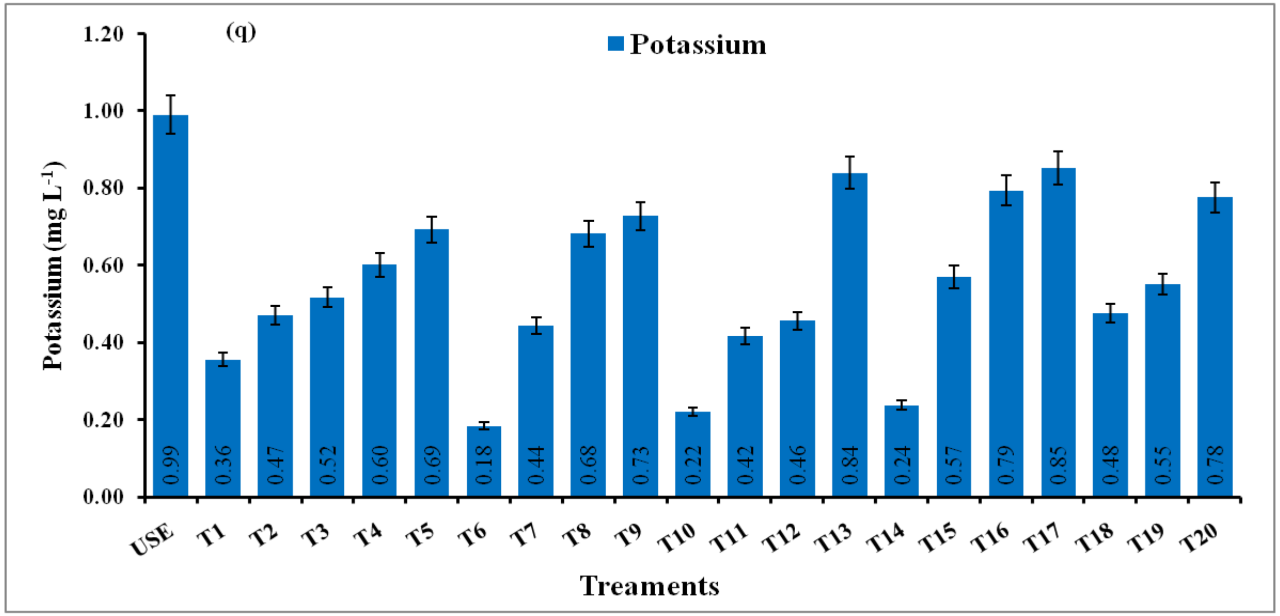

(l)
Ammoniacal-N
Ammoniacal-N (mg L^{-1})
6.00
5.00
4.00
3.00
2.00
1.00
0.00
3.83
3.27
4.50
3.10
3.37
2.77
4.87
3.43
2.93
2.97
2.37
1.47
1.70
1.47
2.73
1.40
2.17
2.23
3.63
2.63
2.53
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments


(m)
Nitrate-N
Nitrate-N (mg L-1)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
3.83
3.27
4.50
3.10
3.37
2.77
4.87
3.43
2.93
2.97
2.37
1.47
1.70
1.47
2.73
1.40
2.17
2.23
3.63
2.63
2.53
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments


(n)
Organic-N
Organic-N (mg L-1)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
7.38
0.74
1.25
0.43
0.93
0.82
0.93
1.12
0.82
1.10
1.47
1.82
1.12
1.14
0.63
0.47
0.30
0.20
0.14
0.37
0.19
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments


(0)
■ Total-N
Total-N (mg L-1)
25.00
20.00
15.00
10.00
5.00
0.00
18.38
15.97
15.31
15.97
15.95
16.24
16.57
17.15
15.54
15.59
15.23
14.03
14.69
16.00
16.18
16.44
17.22
17.44
17.28
17.45
17.23
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments


(p)
■ Total phosphorus
Total phosphorus (mg L-1)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
10.50
7.38
6.46
7.29
6.67
4.67
4.48
4.51
4.51
5.65
4.51
4.59
5.13
5.12
4.93
4.69
4.63
4.85
4.75
4.90
4.73
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treatments


(q)
Potassium
Potassium (mg L^{-1})
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.99
0.36
0.47
0.52
0.60
0.69
0.18
0.44
0.68
0.73
0.22
0.42
0.46
0.84
0.24
0.57
0.79
0.85
0.48
0.55
0.78
USE
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
Treaments

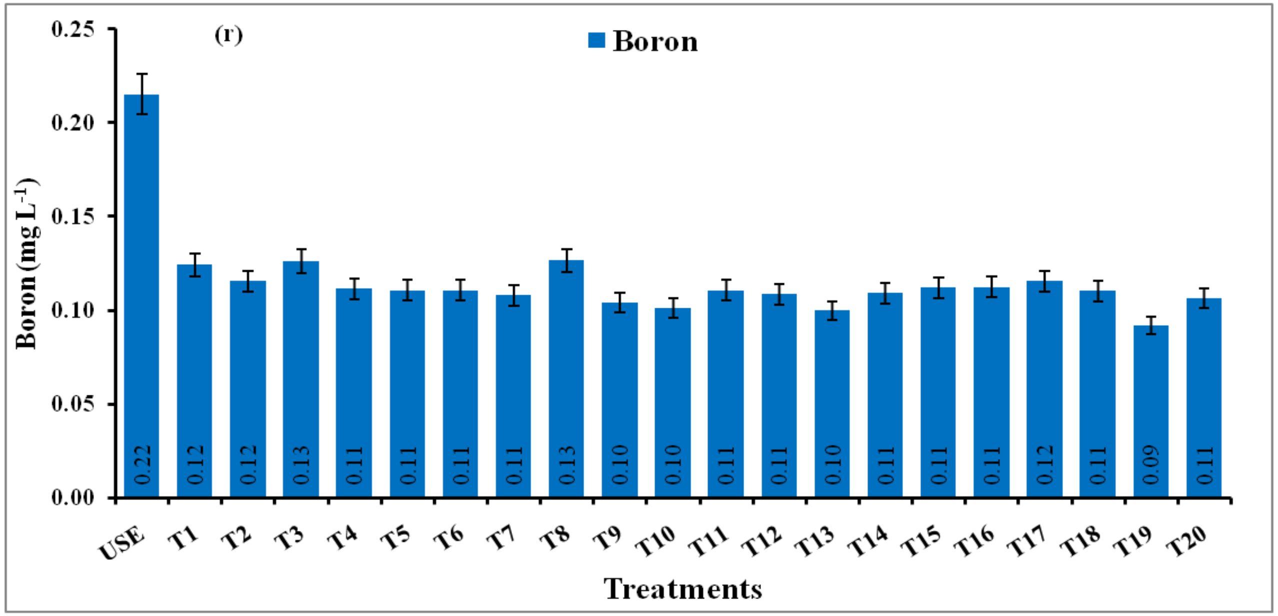


Fig. 3. Sewage effluent quality

Sewage effluent quality (a) pH, (b) EC, (c) TDS, (d) TSS, (e) TS, (f) BOD, (g) COD, (h) Sodium, (i) SAR, (j) Bicarbonate, (k) RSC, (l) Ammonical-N, (m) Nitrate-N, (n) Organic-N, (o) Total-N, (p), Total-phosphorus, (q) Potassium, and (r) Boron, influenced by 20 treatment combinations of five filter beds (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 sp.) as USE= Untreated sewage effluent, T1= Gravel + Typha, T2= Gravel + Paragrass, T3= Gravel + Canna, T4= Gravel + Phragmites, T5= Gravel-Sand-Gravel + Typha, T6= Gravel-Sand-Gravel + Paragrass, T7= Gravel-Sand-Gravel + Canna, T8= Gravel-Sand-Gravel + Phragmites, T9= Gravel-Sand-Brick-Gravel + Typha, T10= Gravel-Sand-Brick-Gravel + Paragrass, T11= Gravel-Sand-Brick-Gravel + Canna, T12= Gravel-Sand-Brick-Gravel + Phragmites, T13= Gravel-Sand-Charcoal-Gravel + Typha, T14= Gravel-Sand-Charcoal-Gravel + Paragrass, T15= Gravel-Sand-Charcoal-Gravel + Canna, T16= Gravel-Sand-Charcoal-Gravel + Phragmites, T17= Gravel-Sand-(Charcoal+Brick)-Gravel + Typha, T18= Gravel-Sand-(Charcoal+Brick)-Gravel + Paragrass, T19= Gravel-Sand-(Charcoal+Brick)-Gravel + Canna, and T20= Gravel-Sand-(Charcoal+Brick)-Gravel + Phragmites

3.1 pH

The lowest effluent pH was recorded in the '*gravel-sand-(charcoal+brick)-gravel'* filter bed (7.18). Constructed wetland vegetated with *Phragmites* was most efficient in reducing pH compared to other macrophytes (Table 4 and Fig. 3a).

Across treatments, the reduction in pH after 120 days was 11.4% compared to PTSE. Similar observation was made by Rajimol et al. [13]. The observed pH reduction was attributed to CO_2 production from decomposing plant litter, dissolved organic matter, and other sewage effluent components trapped in the root mat and nitrification of ammonia [14]. The presence of considerable calcium+magnesium (SAR < 5) in PTSE (Table 3) and its alkaline pH favors the precipitation of these alkaline metals as their carbonates and phosphates when it is stranded in the wetland. That might be the reason for the general lowering of pH of treated sewage effluents. Similar reasoning was reported by Priya et al. [15]. They are opinioned 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 the SAR was not increased rather it decreased possibly due to the lowering of sodium also through adsorption on filter bed materials and uptake by macrophytes. The reduction in EC of treated sewage effluent over PTSEsupported this fact (Table 3). The presence of brick and charcoal as filter bed materials in addition to sand and gravel might have favoured such reactions.

3.2 Electrical Conductivity (EC)

The EC values for filter beds and macrophytes varied only slightly (Table 4). Among filter beds, '*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 the PTSE (2.00 dS m^{-1}). The decrease in conductivity was attributed to the uptake of micro and macro elements and ions by plants and bacteria, and their removal through adsorption to plant roots, litter and settle able suspended particles [16,14], and due to the precipitation.

The '*gravel-sand-(charcoal+brick)-gravel'* filter bed caused a greater reduction in EC compared to others. Looking at the composition of this filter bed, it seemed the 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* favored a 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 and Fig. 3b)

3.3 Total Dissolved Solids (TDS)

Among filter beds, '*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 Fig. 3c).

The solid portion may be in suspended, dissolved, and colloidal states which impart turbidity to the sewage water. The 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 [17].

3.4 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'* filter bed 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 [18,16] (Fig. 3d).

3.5 Total Solids (TS)

The TS at 120 days varied relatively among filter beds (901 to 966 mg L^{-1}) and macrophytes (838 to 999 mg L^{-1}). The '*gravel-sand-charcoal-gravel'* among filter beds, while *Brachiaria* among macrophytes was more efficient in lowering TS (Table 4 Fig. 3e). The interaction between the filter beds 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).

3.6 Biological Oxygen Demand (BOD_5) and Chemical Oxygen Demand (COD)

The BOD_5 concentration of treated effluent was significantly reduced due to filter beds and macrophytes (Table 4; Figs. 3f and 3g). The filter bed '*gravel-sand-(charcoal+brick)-gravel'* (92.1 mg L^{-1}) reduced more BOD_5 concentration compared to other filter beds. The BOD_5 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 BOD_5 (88.3 mg L^{-1}).

Among the filter beds, '*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 Oliete et al*.* [19]. A similar reduction through wetland was also reported by Jizheng et al. [20]. 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} [21]. After allowing the raw sewage effluent to flow through the wetland system, there was a reduction in its BOD_5. Zurita et al. [18] reported a higher BOD_5 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 [22]. Similar findings were reported by Li et al. [23], Vera et al. [16], and Kelvin and Tole [24]. The same reason could be attributed to the notable decline in the COD of treated sewage effluent since both COD and BOD measure 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 the rhizosphere meeting the oxygen demand for the chemical oxidation of organic constituents. According to MoEF standards, COD of a maximum of 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.

3.7 Sodium

A greater reduction in sodium concentration in treated effluent was observed in '*gravel-sand-charcoal-gravel'* among filter beds and *Typha* among macrophytes (Table 5 and Fig. 3h). 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 was reduced to 4.57 meq L^{-1} due to wetland treatment with a 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 meqL^{-1} for irrigation [21]. The reduction in sodium concentration was accredited to the processes of sedimentation, filtration, decomposition, adsorption, and plant uptake.

3.8 Sodium Adsorption Ratio (SAR)

Among filter beds, '*gravel-sand-charcoal-gravel'* caused a 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 and Fig. 3i). The reasons for the reduction of SAR in the treated sewage effluent are ingrained in the cause of the reduction of sodium.

3.9 Bicarbonates

The filter bed, *'gravel-sand-charcoal-gavel'* (7.08 meq L^{-1}) was found to be more efficient in bicarbonate reduction (Table 5 and Fig. 3j). Among macrophytes, *Brachiaria* (9.23 meq L^{-1}) was found to be 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} [21].

3.10 Residual Sodium Carbonate (RSC)

Among filter beds, *'gravel-sand-charcoal-gavel'* (RSC 1.94 meq L^{-1}) composition was more efficient in lowering RSC (Table 5 and Fig. 3k). The trend between macrophytes remained similar to that observed under bicarbonate concentrations. Except for *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 (1.40meqL^{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 filter beds whereas the macrophytes *Canna* consistently proved more efficient in reducing RSC.

3.11 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 are concurrently represented by higher BOD values.

In this study, *'gravel-sand-(charcoal+brick)-gravel'* filter bed registered significantly higher ammoniacal nitrogen (NH_4^+-N) and nitrate-nitrogen (NO_3^- -N) as compared to other filter beds. The results are confirmed by Guo et al. [25]. This also registered significantly lower organic N. This implied that the *'gravel-sand-(charcoal+brick)-gravel'* filter bed facilitated higher oxidative conditions resulting in lower levels of organic N and higher levels of inorganic N forms. The same treatment also witnessed a greater reduction in BOD. Among macrophytes, *Typha* registered a higher NH_4^+ -N concentration (13.24 mg L^{-1}) while phragmites had higher NO_3^- -N (2.40 mg L^{-1}) in treated sewage effluent (Table 5 and 6). The NH_4^+ -N concentration in the treated sewage effluent at 120 days remained almost similar to that of PTSE. However, the NO_3^- -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 6; Fig. 3(l) to 3(o)). A similar higher reduction in organic N, amounting to 50.6% was witnessed by Zurita et al. [18] for a vertical flow constructed wetland.

Vymazal [26] reported that a lower hydraulic retention time and greater oxidation in the rhizosphere of macrophytes created more conducive conditions for faster ammonification process leading to the conversion of organic N to NO_3^- -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 the complementary effect of filter bed and macrophyte favored chemolitho autotrophic microbial activity which led to the conversion of NH_4^+-N to NO_3^--N. The percentage reduction in organic nitrogen in the treated sewage effluent did not exactly match with the percentage increase in NO_3^--N, obviously due to concomitant uptake by macrophytes.

The total N (TN) concentration registered a 35.2% reduction as compared to raw sewage effluent. Comparable results were reported by Kelvin and Tole [24] who reported a removal efficiency of 41 percent for TN. These reductions were mediated by nitrifiers such as Nitrosomonas, Nitropira, Nitrosococcus, and Nitrobacter in both surface and subsurface flow constructed wetlands [27]. The reduction in total nitrogen could also be attributed to the process of adsorption of ammoniacal nitrogen on filter bed materials. Among the macrophytes, *Brachiaria* and uptake by macrophytes (Fig. 3). The results are confirmed by Minakshi et al. [28].

3.12 Total Phosphorus (TP)

The *'gravel-sand-gravel'* (4.54 mg L^{-1}) filter bed reduced more TP compared to others (Table 5).

It might be due to the lower effective size of filter bed materials which includes sand as a major component. It is evident from Table 1 that sand with minimum size had greater surface area among the filter bed materials accounting for greater adsorption. A similar finding was reported by Seo et al. [29]. The most important characteristic of the filter bed 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 favored precipitation with P as sparingly soluble calcium phosphates particularly in the slightly alkaline conditions, typical of domestic sewage [30].

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 the root surface taking place in the wetland treatment system. The results were in accordance with the findings of Neralla et al. [31], Vera et al. [16] and Arivoli and Mohanraj [14] (Fig. 3p). Plant species, hydraulic retention time, temperature, type of constructed wetlands, effluent concentration and seasonal changes can influence the removal efficiency of phosphorus in constructed wetlands [32].

3.13 Potassium

The filter beds, *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 and Fig. 3q). The K removal was less in filter beds involving charcoal indicating that charcoal might have contributed to K during wetland treatment. The *Brachiaria* (12.40 mg L^{-1}) was found to be highly effective in K removal compared to other macrophytes which also witness the highest K uptake among macrophytes. The *Brachiaria* planted in *the 'gravel-sand-gravel'* filter bed significantly reduced potassium (7.15 mg L^{-1}).

A 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 filter beds, *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 filter beds involving charcoal indicating that charcoal might have contributed to K during wetland treatment. The *Brachiaria* (12.40 mg L^{-1}) was found to be highly effective in K removal compared to other macrophytes. The *Brachiaria* planted in *the 'gravel-sand-gravel'* filter bed significantly reduced potassium (7.15 mg L^{-1}).

3.14 Boron

The filter beds 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 was 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 time it was well below the safe limit. Filtration, adsorption, and plant uptake might have contributed to the reduction of B in the treated sewage effluent [26]. Though Turker et al. [33] 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 (Fig. 3r) [34].

4. CONCLUSION

The inclusion of brick and/or charcoal as filter bed material in addition to sand and gravel has improved the physical filtration capacity of the wetland system. Looking at the differential biological filtration ability of macrophytes, the 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), a suitable combination of filter beds and macrophyte may be resolved. The flexibility of the selection of filter bed and macrophyte allows the wetland to be adapted to different sites. This flexibility also allows adapting suitable macrophytes in the primary, secondary, or tertiary treatment stage. The constructed wetland treatment reduced pH, EC, total nitrogen, organic nitrogen, total phosphorus, SAR, RSC, boron, TSS, TDS, TS, BOD, COD and bicarbonates by more than 40 per cent. However, resulted in higher ammoniacal and nitrate nitrogen in the treated sewage effluent

The findings of this study highlight the use of a vertical constructed wetland system with filter beds and macrophytes, which have a beneficial impact on treating domestic sewage water and its re-use for crop production, especially in water scarcity areas.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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