Phytoremediation: An effective technique for domestic wastewater treatment in developing countries

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Research Article

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Abstract

Phytoremediation in the form of constructed wetlands is an effective method of treatment of municipal as well as industrial wastewater. The efficacy of this method has already been tested in European and American countries and found to be the best method of wastewater treatment. Efforts have been made in the present work to check the efficacy of phytoremediation in the form of constructed wetlands under Indian climatic conditions. A pilot plant of constructed wetlands has been constructed on the premises of the Uttaranchal Jal Nigam Sewage treatment plant and municipal wastewater has been allowed to pass through the constructed wetland. It has been observed that BOD removal at 24 °C is governed by the equation \( \frac{C_e}{C_0} = e^{-1.0042 \times t} \) and the removal rate constant of BOD has been observed to be 0.795 d\(^{-1}\) at 20 °C. It has been observed that the pilot-constructed wetland is bringing effluent BOD and TSS up to 20 mg/l and 30 mg/l respectively consistently for the duration under study. The values of hydraulic retention time, hydraulic loading, and organic loading for achieving this performance are found to be 1.75 days, 13.22 cm/d, and 142.78 kg/ha. d respectively. Performance study of constructed wetland and the existing activated sludge treatment has shown that the percent removal for the parameters TSS, BOD, COD, and Fecal Coliforms is near to the same order except for TN and TP, where the activated sludge process unit shows higher removal than the constructed wetland.

1. Introduction

1.1 Location of constructed wetlands site

Phytoremediation in the form of wetlands is the natural method for the removal of impurities from wastewater. The aquatic vegetation is performing the task of wastewater treatment since the inception of the earth. Constructed wetlands have reportedly been used and found to be most efficient in the treatment of wastewater in various countries like the Czech Republic (Vyamazal 2010) China (Xiangyu et al., 2020), France (Morvannou A et al., 2015), Oman (Stefanakis, 2020), because of checking the efficacy of this treatment in a temperate zone like India, the efforts are being taken to compare the constructed wetland, a natural treatment by constructing a pilot plant and conventional activated sludge treatment. The pilot plant constructed wetland site is located on the premises of Uttarakhnad Jal Nigam sewage treatment plant at Haridwar in north India. It is about 30 km from IIT Roorkee. This site was selected considering the following advantages:

The domestic wastewater (raw as well as treated) in the required quantity was available round the clock at the wetland site. A sufficient head was available to get the wastewater by gravity at the site hence the cost of pumping could be avoided. A comparison of the performance of constructed wetlands could be attempted with the performance of the activated sludge treatment process. Well-equipped laboratory facilities were available at the site to store and preserve the wastewater samples whenever needed.

Wastewater after preliminary treatment was tapped at the overhead distribution channel and diverted to constructed wetland site through a 250 m long and 50 mm diameter underground PVC pipeline as shown in Fig. 1. The effluent after treatment was disposed-off in the existing outlet channel of the treatment plant.

1.2 Collection of Wastewater

In the town of Haridwar, wastewater is presently being collected through the network of a sewerage system. Open channels in town join the underground sub-main and finally the main sewer line. The main sewer line feeds their discharge to the wet well located in different areas of town after passing through the racks and screens. The wastewater is retained here for some time and pumped to the main pumping station at the scheduled time. Eleven such pumping
stations are established in different parts of town. The location of the main pumping station is about four km away from the town. The wastewater again undergoes preliminary treatment through rack and screen after entering the premises of the main pumping station. A set of two pumps 80 HP each and another set of two pumps 40 HP each have been installed at the main pumping station. These pumps are operated in turns depending upon the inflow of wastewater. Some amount of this discharge is supplied directly to the sewage farms for irrigation whereas 24 MLD wastewater is pumped to the plant for treatment.

1.3 Existing Treatment Method

The detailed layout plan of the existing activated sludge process and the constructed wetland treatment pilot scale plant is shown in Fig. 1. Wastewater initially passes through preliminary treatment units. The preliminary treatment consists of a mechanical rack and screen where the floating and other discrete impurities like tobacco pouch, trash, silt, etc. are arrested and separated from wastewater. The wastewater then flows through the overhead distribution channel. This channel performs two functions:

1. It has a partial flume that measures wastewater discharged by the treatment plant.
2. It distributes discharge uniformly over three units of the activated sludge process

The wastewater subsequently enters into the circular primary and secondary settling tanks with an aeration tank in between them. After treatment, wastewater enters into a collecting channel, from where it is disposed of in the river Ganga. The conventional activated sludge treatment plant was constructed in 1980 with a design capacity of 24 MLD. Each unit of the activated sludge process has a capacity of 8 MLD (totaling about 24 MLD by three units). However, presently because of an increase in population, wastewater generated in town is of the order of 35 MLD. Because of this increase in load, the proposal for augmentation of the plant is presently under consideration.

2. Material And Method

2.1 Comparison of Constructed Wetland with Conventional Treatment

The comparison of constructed wetlands with conventional treatment units has been done based on the following aspects.

2.2 Comparison concerning pollutant removal

2.2.1 Micro Flora and Fauna: - The degree of abatement achieved in constructed wetlands is much higher as the number of micro-organisms (more than 2000 types of bacteria, protozoa, yeasts, and more than ten thousand fungi and algae) present in the bed is several times more (Trivedy, 1998) than in the case of conventional treatment units.

2.2.2 Pathogen Removal: - It is found that the significant removal of the pathogen can be achieved in constructed wetlands as compared to conventional treatment processes. (Lambe and Whitman 1987; Trivedy 1998; Verma Mahesh et al., 2021; Hilley 1995)

2.2.3 Variation in the handling of pollutants: - Constructed wetlands can remove a variety of pollutants in comparison to the conventional treatment methods/units. This is because a large number of microorganisms are available for
2.2.4 Chemical Requirement: - Use of chemicals in constructed wetlands is rare whereas it is quite frequent in conventional treatments for pH adjustment, flocculation, etc.

2.2.5 Sulfur Removal: - Sulphates are degraded into elemental non-toxic Sulphur in constructed wetlands whereas in conventional treatment units these compounds are converted into toxic sulfides.

2.2.6 Nitrogen and phosphorus Removal: - Reduction of Nitrogen and Phosphorus is reported to be lower in horizontal flow type CW, but comparable in the case of vertical flow type CW and the conventional treatment units.

2.3 Comparison concerning cost

2.3.1 Cost of Construction: - Cost of construction of constructed wetlands (USEPA 1993) & (Vyamazal 2010) is reported to be much less because they are simple to construct require unskilled or semi-skilled labor and use locally available material. On the other hand, the cost of construction of conventional treatment is very high because of the involvement of factors like; huge civil work (earthwork, masonry, etc.), and the construction of facilities. It needs a large amount of expenditure to establish the process, fabrication/procurement/fixation of mechanical and electrical parts, equipment, establishing connectivity, etc.

2.3.2 Cost of Operation and Maintenance: - A few unskilled laborers can achieve the operation of constructed wetlands. Further, the requirement for electrical and mechanical energy is negligible. On the other hand, highly skilled laborers are required and a large amount of electrical and mechanical energy is required for operating the conventional treatment units. As the number of equipment is used in the conventional processes, their maintenance in terms of frequent repairs, and wear and tear also involves an additional expenditure. Therefore, the overall cost of operation and maintenance in the case of conventional treatment is much more than constructed wetlands.

2.4 Ancillary Benefits

“Although the main aim of constructed wetlands is to treat the wastewater, in addition to this, there are many more benefits of these wetlands to the public and wildlife habitats like (Knight 1997)

a. Animal diversity in surface flow treatment wetlands typically incorporates the full range of groups found in large wetlands, including microscopic invertebrates, macroinvertebrates, fishes, reptiles, amphibians, birds, and mammals.

b. Constructed wetlands have been utilized for direct human life support. Some of the large constructed wetlands are open for hunting

c. Wetland vegetation like common reeds after harvesting can be used as thatch for roofing

d. Some wetlands are attractive habitats for furbearers such as *Onadilla zibethica*, *Myocastor*, *Coypus*, etc.

e. The big wetlands are beneficial for recreational activities such as hiking, jogging, biking, and wildlife study.

f. Constructed wetlands in some cases are used as outdoor laboratories”

2.5 Pollutant Removal Mechanisms
The accomplishment of removal of pollutants in a constructed wetland (Sundaravadivel and Vigneswaran, 2001) is believed to happen in the following ways:

a. Uptake of pollutants directly by the plants
b. Plants, as well as substrate media, offer a large surface area for the proliferation of microorganisms that degrades pollutants.
c. Sedimentation of solids occurs because of the decreasing velocity of flow while flowing through the wetland
d. Large particles are removed through root and reed masses
e. Nutrients like nitrates and phosphates are adsorbed by soil and substrate
f. Detention time of wetland allows natural die-off of pathogens
g. UV radiation and excretion of antibiotics by plants to destroy pathogens

Interaction with wetland vegetation, the water column, and the wetland substrate results in pollutant removal in the wetland. Table 1 shows the type of pollutants and removal processes. These processes may be categorized as physical, chemical, and biological processes and described below:

Table 1: Pollutant Removal Processes in Constructed Wetlands

<table>
<thead>
<tr>
<th>Sr. No. (1)</th>
<th>Pollutant (2)</th>
<th>Removal Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Organic Material</td>
<td>Biological degradation, sedimentation, microbial uptake</td>
</tr>
<tr>
<td>2</td>
<td>Organic contaminants such as Pesticides</td>
<td>Adsorption, volatilization, photolysis, and biotic/abiotic degradation</td>
</tr>
<tr>
<td></td>
<td>Suspended Solids</td>
<td>Sedimentation, filtration</td>
</tr>
<tr>
<td>3</td>
<td>Nitrogen</td>
<td>Sedimentation, volatilization,</td>
</tr>
<tr>
<td>4</td>
<td>Phosphorus</td>
<td>Nitrification/denitrification, microbial uptake, plant uptake</td>
</tr>
<tr>
<td>5</td>
<td>Pathogens</td>
<td>Sedimentation, filtration, adsorption, plant and microbial uptake</td>
</tr>
<tr>
<td>6</td>
<td>Heavy Metals</td>
<td>Natural die-off, sedimentation, filtration, predation, UV degradation, adsorption</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Sedimentation, adsorption, plant uptake</td>
</tr>
</tbody>
</table>

2.5.1 Physical Processes

The availability of plant biomass and substrate media helps in physical pollutant removal processes in wetland systems. Plants physically slow down the pathways of wastewater enhancing the sedimentation of suspended solids. The media like sand or gravel acts as a filter for the infiltration process, thereby aiding the physical removal of suspended solids through straining.

2.5.2 Chemical Processes
Chemical reactions between substances especially metals, lead to their precipitation in the form of insoluble compounds. Exposure to atmospheric gases and sunlight also leads to the breakdown of organic pesticides and the destruction of pathogens. Antibiotic chemicals expelled by plants also play an important role in the removal of pathogens present in wastewater.

### 2.5.3 Biological Processes

Constructed wetlands are biological systems in which biological processes play an important role in the removal of pollutants. Six major biological reactions namely photosynthesis, fermentation, respiration, denitrification, nitrification, and phosphorus removal have been identified as aiding the pollutant removal performance of wetland systems.

Wetland vegetation performs photosynthesis which results in the removal of organic carbon from the water column and also adds oxygen to wastewater. Oxygen breathe out by plant leaves during photosynthesis may increase the partial pressure of oxygen in the atmosphere close to the water surface, and enhances its diffusion into water. Floating or submerged plants present in wetlands directly breathe out oxygen into the water. Oxygen, while assisting the biological degradation of organic pollutants also drives the nitrification process.

During breathing, oxygen coming out through the root hairs may create an oxygen-rich area around the root zone of plants. This oxygen leakage helps in maintaining partial aerobic conditions in the water column (Hilley, 1995). Fermentation refers to the breakdown of organic carbon in the absence of oxygen into compounds like alcohol, methane, and volatile fatty acids. Fermentation is stimulated by the metabolic activities of microorganisms present in the water column and sand or gravel media.

Denitrification and Nitrification processes are mediated by the microbes and result in the elimination of nitrogen from wastewater. While assisting the bio-degradation of organic pollutants, oxygen in amalgamation with carbon drives the process of nitrification. The process of volatilization removes nitrogen in treatment through wetlands. The background developed in the aerobic and anaerobic environment also helps in achieving nitrification and also denitrification at the same time.

Phosphorus removal occurs in biofilms developed on the substrate and microorganisms existing in sediments. The plant takes up the dissolved matter and a variety of other pollutants from wastewater and changes them into additional plant biomass. The pollutants and nutrients then move through the body of the plant to underground storage organs. When the plants become old and die, they are left in the sediments as peat and litter. Microorganisms present in the wetlands system including fungi and bacteria stabilize and remove colloidal and dissolved organic matter by altering them into different gases and cell tissues. Most of the organisms in wetlands are identical to that occur in conventional biological treatments.

### 3. Present Study

#### 3.1 Construction Details of Wetlands

Two beds of horizontal flow type constructed wetlands were constructed at the site as shown in Fig. 2. One bed was used for studies on raw domestic wastewater and the other bed for studies on improving wastewater quality already treated by the activated sludge process.

A brick masonry manhole was constructed at the inlet end of the bed. It was provided with a constant head tank facilitating uniform flow in the bed. The control valve provided in the manhole regulates the flow. Wastewater was
uniformly distributed by perforated pipe placed semi-circular PVC channel wherein V-notches were cut at 10 cm intervals.

The outlet chamber of brick masonry was constructed at the farther end of the bed. A flexible pipe provided at the end of the collection pipe helps in controlling the wastewater level in the bed. The wastewater after treatment was collected in a 75 mm diameter perforated pipe provided at the bottom of the bed at the outlet and taken into the outlet chamber. The treated wastewater is then disposed of in the main drain carrying treated wastewater from the existing sewage treatment plant. The Inlet and outlet zones of the bed were 50 cm wide and filled with gravel of size 20 to 80 mm. The construction of the pilot scale constructed wetland bed is also shown in photograph 1.

The soil texture available at the site was silty clay having a hydraulic conductivity of the order of $10^{-8}$ m/s. Although the hydraulic conductivity of the bed was very low, still as a factor of safety, two layers of polyethylene sheet having a thickness of 0.30 mm were laid at the bottom and sides of the bed.

The natural sand in the riverbed was not suitable for the wetland bed. Sieve analysis was carried out (Lambe and Whitman, 1987) for removing too fine and too coarse portions of natural sand. The effective size ($d_{10}$) of 0.8 mm and the Uniformity Coefficient ($d_{60}/d_{10}$) of 8.52 was calculated for the dressed sand. Filter media and gravel were then filled simultaneously in different layers in the bed. The coefficient of permeability ($K_f$) of filter media has been calculated from the effective size ($d_{10}$) in mm of the media by the relation \[ K_f (m/s) = (d_{10})^2 / 100 \] given by Hazen (Terzaghi and Peck, 1956; Punmia, 1994) and found to be $6.4 \times 10^{-3}$ m/s.

An exhaustive study of vegetation was carried out in and around the area. The existing bogs, marshes, and natural wetlands were surveyed for the study of macrophytes. The \textit{Phragmites karka} was found to be the most efficient and hardy plant and hence used at the project site.

### 3.2 Monitoring Programme

#### 3.2.1 Effect of Hydraulic Loading on Removal

The studies have been carried out on constructed wetland units and the results obtained are discussed in the following sequence:

3.2.1.1 Estimation of BOD removal rate constant ($K_d$) of the treatment system.

Estimation of HRT, discharge, hydraulic loading rate, and organic loading rate at a residual BOD (in the effluent) of 20 mg/l, as per the BIS Standards (BIS, 1973) for effluent disposal in surface water bodies.

3.2.1.2 Comparison of removal efficiency of constructed wetland with activated sludge treatment.

Hydraulic loading is defined as the quantity of wastewater in liter per day applied to the unit area of the bed. It can also be represented in terms of cm/d. It gives an idea about the depth of water uniformly applied to the wetland surface over a specified time interval.

Mathematically, it is represented as

\[
\text{Hydraulic Loading Rate (l/m2. d)} = \frac{\text{Discharge (l/d)}}{\text{Plan Area (m2)}}
\]

The reported range of HRT for subsurface constructed wetlands (Crites, 1994) is between 2 to 7 days. While conducting the present study on the constructed wetland research site at Haridwar, the bed was set at the hydraulic loading...
corresponding to HRT ranging from 1 to 4 days at an interval of 1 day in decreasing order. It was practically not possible to set the discharge corresponding to HRT greater than four days, because of the hindrance caused by floating impurities at low flows resulting in frequent choking of constant head tank outlet. After setting the bed for a particular hydraulic retention time, the bed was allowed to stabilize for two months as it was observed to result in a uniform outlet BOD concentration. The inlet and outlet wastewater samples were then collected daily for five days and transported to the water quality laboratory for analysis. Corresponding to the HRT of 4 days, the discharge, hydraulic loading rate, and organic loading rate were 0.88 m³/d, 58.17 l/m².d (6 cm/d) and 6.28 g/m².d (62.8 kg/ha.d) respectively.

Similarly, for the HRT of 1 day, discharge, hydraulic loading, and organic loading were 3.5 m³/d, 24 cm/d, and 250 kg/ha.d respectively. The remaining values fell in between the above range as shown in Fig. 3 and presented in Table 2.

Table 2: Average percent removal of parameters in raw bed at various hydraulic loadings

<table>
<thead>
<tr>
<th>HRT (d)</th>
<th>Discharge (m³/d)</th>
<th>Hydraulic Loading (cm/d)</th>
<th>Organic Loading (kg/ha.d)</th>
<th>Average Percent Removal (n = 5, σ = ±15)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TS (5)</td>
</tr>
<tr>
<td>4</td>
<td>0.88</td>
<td>6</td>
<td>62.5</td>
<td>39.45</td>
</tr>
<tr>
<td>3</td>
<td>1.17</td>
<td>8</td>
<td>83.5</td>
<td>37.29</td>
</tr>
<tr>
<td>2</td>
<td>1.75</td>
<td>12</td>
<td>125</td>
<td>31.29</td>
</tr>
<tr>
<td>1</td>
<td>3.5</td>
<td>24</td>
<td>250</td>
<td>28.79</td>
</tr>
</tbody>
</table>

3.2.1.3 Determination of BOD Removal Rate Constant

It was observed that the effluent BOD concentration in wastewater decreases with an increase in retention time. The data has been analyzed to check the variation in the ratio of effluent to influent BOD (i.e. \( C_e/C_o \)) with change in hydraulic retention time.

A first-order plug flow model for BOD removal has been reportedly used in earlier studies for the design of SF wetland systems. The general form of the model used in the United States, Europe, and Australia is presented below:

\[
Ce/Co = e^{-Kt.t}
\]

Where,

\( C_e \) = effluent BOD (mg/l) \( C_o \) = influent BOD (mg/l) \( K_t \) = rate constant (d⁻¹)

\( t \) = hydraulic retention time (d)

The rate constant is temperature-dependent and follows van't Hoff Arrhenius equation:

\[
Kt = K_{20} (θ) T^{-20}
\]

Where

\( K_{20} \) = BOD removal rate constant at 20 °C (d⁻¹)
\(T\) = Temperature of liquid in the system 0\textdegree C

\(\theta\) = Temperature activity coefficient

The temperature activity coefficient of 1.06 is indicated by EPA (USEPA, 1993; USEPA, 1988), hence the same value has been used for converting the decay rate constant from 24 \textdegree C to 20 \textdegree C in the present study.

The value of the rate constant \(K_{20}\) used in the above equation for the design of surface flow constructed wetlands has been reported to lie in the range of 0.8 to 1.104 d\(^{-1}\) (USEPA, 1988; WPCF, 1990; Crites, 1994). It is believed that; the rate constant for subsurface flow wetlands is higher than those for facultative lagoons or free water surface flow wetlands because of the availability of more surface area of the media. This surface area supports the development and retention of attached growth microorganisms, which are believed to provide most of the treatment responses in the system.

The coefficient \((C_e/C_o)\) has been calculated for different hydraulic retention time values as presented in Table 3. A graph between \(C_e/C_o\) and hydraulic retention time \(T\) has been plotted as shown in Fig. 4. Non-linear regression of the data has yielded the following equation, which indicates the estimate of constant \(K_f\) at 24 \textdegree C as 1.0042 d\(^{-1}\).

\[Ce/Co = e^{1.0042 \times t}\]

The value of \(K_f\) at 20 \textdegree C standard temperature has been calculated as:

\[K_{24} = K_{20} \times (\theta)_{24-20}\]

\[K_{20} = K_{24}/(\theta)_{24-20}\]

\[K_{20} = 1.0042 / (1.06)^{24-20}\]

\[= 0.795 \text{ d}\_\text{\textsuperscript{-1}}\]

The value of the removal rate constant \((K_{20})\) estimated as above for the present study is close to the range of 0.8 to 1.1 d\(^{-1}\) and is well supported by earlier studies (Crites, 1994; USEPA, 1988; WPCF, 1990; Hammer, 1989; Cooper, 1990; Bavor et al., 1988; Reed and Brown, 1992; Conley et al., 1991; Cooper and Hobson, 1990) (Crites, 1994; Cooper, 1990; Bavor et al., 1988; Reed and Brown, 1992; Conley et al., 1991; Cooper and Hobson, 1990).

Table 3: First Order BOD \((n = 15, \sigma = \pm 15)\) Removal Rate Constant \((K_f)\)
3.2.1.4 Determination of discharge, retention time, hydraulic loading, and organic loading at an effluent BOD of 20 mg/l

As per the Bureau of Indian Standards (BIS, 1973) guidelines for disposal of wastewater in inland water bodies, the treated effluent should not have a BOD of more than 20 mg/l. It was observed from the experiments that the effluent BOD decreases with an increase in retention time. A graph between effluent BOD ($C_e$) and hydraulic retention time indicates the trend as shown in Fig. 5. To ensure that the pilot-constructed wetland unit operates by BIS norms, the HRT required to get the effluent BOD of 20 mg/l was determined from this figure. It was found that the hydraulic retention time of 1.75 days is sufficient for bringing the effluent BOD to 20 mg/l by the employed horizontal subsurface flow constructed wetland system. The respective discharge, hydraulic loading rate, and organic loading rate have been calculated as given below:

\[
\text{Discharge} = \frac{\text{Length} \times \text{Width} \times \text{Depth} \times \text{Porosity}}{\text{Hydraulic Retention Time}}
\]
Discharge = \((4.88 \, m \times 3.1 \, m \times 0.8 \, m \times 0.29)/(1.75 \, d)\)
= 2.00 m\(^3\)/d

Hydraulic Loading = \(\text{Discharge}/\text{Area}\)

Hydraulic Loading = 2000 \((l/d) \times 4.88 \,(m) \times 3.1\,(m)\)
= 132.21 l/m\(^2\). d (13.22 cm/d)

Organic Loading = \(\text{BOD} \times \text{Discharge}/\text{Plan Area}\)

Organic Loading = 108 \times 2/4.88 \,(m) \times 3.1\,(m)
= 14.28 g/ m\(^2\). d (142.8 Kg/ha. d)

The estimated value of a desirable hydraulic retention time of 1.75 days is close to the range of 2-7 days recommended by various researchers. It has also been reported (USEPA, 1993) that several horizontal sub-surface flow constructed wetlands in the US (Mandeville 0.9 d, Monterey 0.9 d, Greenleaves Subdivision 1.0 d) are successfully operating at hydraulic retention time values close to the estimated value in this study.

3.2.1.5 Comparison of Constructed Wetland with Activated Sludge Treatment

Samples were collected at a weekly interval from the inlet and outlet chambers of constructed wetland bed and outlet of the secondary settling tank of the existing activated sludge treatment for assessing the performance of both constructed wetland treatment and existing activated sludge treatment. The performance of both constructed wetlands and activated sludge process has been assessed for three months and shown in Table No. 4 and Fig 6.

4. Results And Discussion

After performing various studies, it is observed that Phytoremediation technology has great potential for the purification of wastewater. The performance of constructed wetland has been compared with the performance of the existing activated sludge treatment process employed at the site in terms of the percent removal of impurities. Table 4 presents the data for comparison of constructed wetlands and activated sludge treatment whereas a graphical representation has also been shown in Fig. 6.

From the table, it is clear that the average percent removal of suspended solids is 82 percent in a constructed wetland and 85 percent in the activated sludge process, which is nearly the same in both treatments. Although the percent removal of BOD in the activated sludge process is observed to be more (90.3%) as compared to the constructed wetland (82.7%), the constructed wetland unit, on the other hand, is duly fulfilling the requirement of producing the effluent at the desired standard of 20 mg/l and the effluent of activated sludge treatment has BOD value below 10 mg/l. As far as nutrient removal is concerned, the activated sludge process is found to be more efficient in removing 64.7 percent TN and 32.7 percent TP, whereas the constructed wetland is removing only 23.9 percent and 24.1 percent of Total Phosphorus.

Further, Fecal Coliform removal in the constructed wetland is observed to be comparable with the activated sludge process. However, it may be noted that even with this observed magnitude of removal, the bacteriological effluent standards of 103 no./100 ml as recommended by the World Health Organization are still not met by both, constructed wetlands and the activated sludge process.
Few researchers (Griffin, 1998) have also reported that the coliform removal in two wetland units in England treating secondary effluent, though varied between 40 percent to 90 percent, effluent values did not meet the discharge requirements. Based on the above, it may be stated that the overall performance of constructed wetland nearly matches the conventional treatment.

As far as the cost of treatment is concerned, the installation cost of constructed wetland under Indian conditions has been reported (UNIDO, 1990) to vary from US$ 300 (simple wetland) to US$ 1000 (sophisticated wetland) per m3/d wastewater treated as against the cost of conventional biological treatment at about US$ 700-800 per m3/d wastewater treated. The operational cost has been reported in constructed wetlands as US$ 1-2.5 per m3 of wastewater treated as against the US$ 4-6 per m3 of wastewater treated for conventional biological treatment. The installation and operational costs of constructed wetlands at the present research site were observed to be US$ 450 (excluding the cost of land) per m3/d of wastewater treated and US$ 1.5 per m3 of wastewater treated respectively. Hence, considering the removal efficiency and total cost involved in both systems, it may be concluded that the performance of constructed wetland unit is quite comparable to the activated sludge process at a reasonably lesser cost. One factor of criticism against the constructed wetland technology has often been the large requirements of the land. It was observed that the actual land required for constructed wetland at the research site is around 7.5 m2 per m3/d of wastewater treated whereas, the land required for the activated sludge process at Haridwar comes out to be 0.073 m2 per m3/d of wastewater treated. It shows that the actual land required for treatment using constructed wetlands is about 100 times more than the land required for the activated sludge process. However, the total land reportedly acquired at the U.P. Jal Nigam sewage treatment plant including sludge drying beds, pumping station, offices, garages, workshops, generator room, residential colonies, garden, etc. is around 20 hectares. It may be inferred that there is a large infrastructure associated with conventional treatment than the constructed wetland, the resulting requirement of substantially more land for this purpose. The total land requirement for treatment and infrastructure may not be quite different in both cases.

Table 4: Comparison of percent removal of parameters in the constructed wetland (CW) and activated sludge process (ASP)
<table>
<thead>
<tr>
<th>Date</th>
<th>TDS (mg/l)</th>
<th>TSS (mg/l)</th>
<th>BOD&lt;sub&gt;5&lt;/sub&gt; (mg/l)</th>
<th>TN (mg/l)</th>
<th>TP (mg/l)</th>
<th>FC (no./per 100 ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CW (2)</td>
<td>ASP (3)</td>
<td>CW (4)</td>
<td>ASP (5)</td>
<td>CW (6)</td>
<td>ASP (7)</td>
</tr>
<tr>
<td>07/10/21</td>
<td>12.89</td>
<td>13.59</td>
<td>82.6</td>
<td>87.0</td>
<td>81.2</td>
<td>88.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>81.2</td>
<td>88.2</td>
<td>26.7</td>
<td>67.8</td>
</tr>
<tr>
<td>14/10/21</td>
<td>7.73</td>
<td>6.70</td>
<td>84.4</td>
<td>88.5</td>
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<td>85.0</td>
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5. Conclusion

Although the main objective of this research work was to compare the efficiency of Phytoremediation technology i.e. constructed wetlands and activated sludge process for domestic wastewater treatment. The important conclusions arrived at are:

Percent removal of various impurities in wastewater at different hydraulic retention times and hydraulic loading values shows that the removal of carbonaceous impurities in terms of BOD and Fecal Coliforms is very high (66.73 to 98.5 percent and 97.39 to 99.965 percent respectively), but comparatively the removal of Nitrogen (24.20 to 59.53 percent) is very less. Low Nitrogen removal has been reported elsewhere also and it is mainly attributed to the unavailability of sufficient oxygen for further nitrification and denitrification of nitrogenous impurities. The removal of Phosphorus (8.91 to 28.78 percent) was found to be very less. It has been reported that the amount of Phosphorus taken by vegetation is very less and major removal is achieved in the presence of iron and alumina content in the sand media. This removal can be increased by adding iron and alumina in the form of chemicals in the matrix.

The BOD removal at 24 °C was found to be governed by the equation $C_e/C_o = e^{-1.0042xt}$ and the BOD removal rate constant for this system has been estimated as 0.795 d<sup>-1</sup> at 20 °C. This value is quite close to the range reported in the literature as 0.8 to 1.1 d<sup>-1</sup>.

The pilot scale constructed wetland unit for treating raw wastewater was observed to produce a treated effluent having BOD and TSS less than 20 mg/l and 30 mg/l respectively consistently for the duration under study. The values of
hydraulic retention time, hydraulic loading, and organic loading for achieving this performance are found to be 1.75 days, 13.22 cm/d, and 142.78 Kg/ha.d respectively.

Besides considering a series of decentralized constructed wetlands at various locations, the total area requirement for constructed wetlands at the terminal location may also be broken down into smaller area units, and the cost of transportation of wastewater be reduced substantially.

It may be concluded that the constructed wetland method generally appears to be more economical, environment-friendly, and technically efficient. However, its viability may have to be evaluated for individual cases from several angles before taking an appropriate decision.

Comparison of the performance of constructed wetland unit with the existing activated sludge treatment has shown that the percent removal for the parameters TSS, BOD, COD, and Fecal Coliforms is near the same order except for TN and TP, where the activated sludge process unit shows higher removal than the constructed wetland.

While analyzing cost, the cost involved in the installation, as well as operation and maintenance of the activated sludge process, was observed about 2 to 3 times higher than constructed wetland treatment. Further, the actual area required for treatment by constructed wetland was much higher (approximately 100 times) than the activated sludge process. The requirement of associated infrastructure area for activated sludge process (like offices, garages, residential staff colonies, pumping stations, standby power generation, gardens, etc) was observed to be several times larger than the constructed wetland technology for handling the same flow.

Besides considering a series of decentralized constructed wetlands at various locations, the total area requirement for constructed wetlands at the terminal location may also be broken down into smaller area units and the cost of transportation of wastewater be also reduced substantially.

Finally, the constructed wetlands generally appear to be more economical, environment-friendly, and technically efficient. However, its viability may have to be evaluated for individual cases from several angles before taking an appropriate decision

**Declarations**

Ethical responsibilities of authors

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted

This submission implies that the work described has not been published previously, that it is not under consideration for publication elsewhere, and that its publication is approved by the authors. Publishing Policy

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I confirm that I understand the journal Environmental Monitoring and Assessment is a transformative journal. When research is accepted for publication, there is a choice to publish using either immediate gold open access or the traditional publishing route.
Authors' Contribution

Prof Kailash Harne performed experimental work and write-up given in the content of the manuscript, prepared figures, and tables, as per the requirement and also similarity check, etc.

Prof Himanshu Joshi reviewed/modified the text, tables, and figures given in the manuscript.

Competing Interest

None, I declare that the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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References


Photograph 1

Photograph 1 is available in the Supplementary Files section.

Figures

Figure 1

Sewage treatment plant at Jagjeetpur, Kankhal, Haridwar, and site of constructed wetlands
Figure 2

plan and sectional elevation of pilot-scale
constructed wetlands at research project, Haridwar
Figure 3

Percentage Removal of Various Parameters with Hydraulic Loading in Raw Wetland Bed
Figure 4

Determination of BOD Removal Rate ($K_t$) Constant at 24 °C Temp.

Figure 5

Hydraulic Retention Time Vs Effluent BOD

$y = 96.051e^{-0.933x}$

$R^2 = 0.9392$

HRT for Effluent BOD of 20 mg/l is 1.75 days
Figure 6

Comparison of Constructed Wetland (CW) and Activated Sludge Process (ASP)

Supplementary Files

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- Photograph.docx