Treatment of domestic wastewater by a hybrid natural system
G. R. Munavalli and N. S. Pise

ABSTRACT
The present study addresses performance evaluation of a hybrid natural system comprising of settling tank, sand-gravel filter (SGF), aerated constructed wetland (ACW) and vermi filter (VF) for the treatment of domestic wastewater. The sequential batch experiments were conducted in a pilot-scale experimental set-up. The biochemical oxygen demand (BOD$_5$) was varied from 20 to 120 mg/L and the hydraulic retention time (HRT) used was from 1 to 3 d. The BOD$_5$ removal efficiency was found to be in the range 20–40%, and 40–70%, for 3 d HRT in SGF and ACW/VF, respectively. The efficiency of the system for BOD$_5$ removal was observed to be 80–90% at 3 d HRT and the system was found to be adequate for reducing BOD$_5$ to a value less than 20 mg/L. The effluent can be recycled and used for non-potable purposes in a household. The developed system is a potential option for the decentralized wastewater treatment.

Key words | aerated constructed wetland, BOD$_5$ removal, domestic wastewater, vermi filter

INTRODUCTION
Domestic wastewater contains organic and inorganic matter in suspended, colloidal and dissolved form. The various pollutants present in wastewater are generally degradable, non-degradable and biologically accumulative. Municipal wastewater management is a critical issue in the urban environment. If not managed properly, the related effects may pose a serious threat to the environment. Provision of a sewerage system, sewage treatment and disposal are essential for the proper management of wastewater. Many developing nations cannot afford to construct and maintain costly centralized wastewater treatment plants (CWWTPs). Most cities in developing countries like India do not have sewerage systems and sewage treatment is non-existent or partial or inefficient. The treatment systems wherever they exist are centralized and use conventional aerobic treatment. In both the developed and developing world, at least for new developments, centralized sewage treatment systems may not fulfill sustainable wastewater management requirements in future because of ever-increasing demand. Individual households or clusters of homes can treat their domestic wastewater at source in a decentralized manner so as to reduce the burden on CWWTPs.

Decentralized wastewater systems are an economical alternative to centralized systems. A fully decentralized system would need a natural environment that is capable of absorbing the discharged wastewater. The developed alternative techniques are relatively simple natural aquatic/terrestrial wastewater treatment systems that can be designed to include low-cost sanitation and environmental protection measures. Constructed wetlands (CWs) and vermifilters (VF) are the most promising methods of treating wastewater. However, these systems need to be tested effectively at the pilot scale before implementing at the field scale.

CWs have been used successfully in the past for the treatment of wastewater. Physical, chemical and biological processes combine in wetlands to remove contaminants from wastewater. The CWs used include surface flow, sub-surface flow, aerated and non-aerated types. Numerous

The VF is an improved soil filter colonized by earthworms and bacteria. The soil provides a platform for earthworm development and movement in the VF. Vermifiltration of wastewater using earthworms occurs by the general mechanism of ingestion and biodegradation of organic waste, heavy metals and solids from wastewater, and also by their absorption through body walls. The studies carried out to treat wastewater/sludge using earthworms include Bhawalkar (1996), Taylor et al. (2003), Munavalli & Phadatare (2006), Sinha et al. (2008), Kadam et al. (2009), Dhadse et al. (2010), Zhao et al. (2010), Wang et al. (2010a, b), Xing et al. (2010), Wang et al. (2011a, b), Xing et al. (2011), Li et al. (2011) and Tomar & Suthar (2011).

It can be seen from reviewing the literature that the CW and VF systems have been separately adopted for the efficient treatment of domestic wastewater. However, there is a need to develop, assess the performance and establish design guidelines for a hybrid natural treatment system consisting of primary, secondary and tertiary processes. In the present study, a pilot-scale hybrid natural treatment system consisting of primary treatment (settling tank and sand-gravel filter (SGF)), secondary treatment (ACW with T. latifolia in stone media) and tertiary treatment (VF and coal filter) was developed. The performance evaluation studies were carried out at various stages of treatment for varied organic loading rate and hydraulic retention time (HRT).

MATERIALS AND METHODS

Experimental set-up

The objectives of the system were to remove suspended solids and dissolved organic matter. The processes used in the experimental setup include settling, filtration, decomposition and adsorption. The suspended solids are removed in a settling tank and also in a SGF. The removal of dissolved organic matter occurs by means of the attached growth system in a SGF and the attached and suspended growth system in an ACW. An aerobic environment is maintained within the ACW. Further removal of dissolved organic matter occurs in the VF. The coal filter refines the quality of wastewater through adsorption. The developed experimental setup has a logical sequence of primary, secondary and tertiary treatment processes.

Figure 1 shows a schematic sketch of the pilot-scale treatment system with flow regulation valves. It consists of four units: settling cum equalization tank, SGF, ACW and VF. Each unit has a capacity of 50 L and depth of 54 cm. The settling unit allows the coarser solids to settle out and equalize the quality of feed wastewater. In order to refine the quality of feed water to the ACW, the SGF was provided. It is a graded upflow filter with gravel at the bottom and sand at the top. The details of filter are given in Table 1.

The secondary treatment is in the form of a vertical subsurface flow ACW. It has stone-grit (8–12 mm) as a supporting medium vegetated with T. latifolia. The ACW was provided with a special type of aeration system consisting of an interconnected network of perforated vertical and horizontal pipes to induce the air circulation naturally. There are five vertical pipes provided throughout the depth of medium and six horizontal pipes located at different levels. The tertiary treatment unit has VF followed by layers of coal. Both of these were included in the same tank with the VF at the top and the coal bed at the bottom. The VF is made up of a circular plastic tank of 32 cm diameter and 48 cm height. The bottom of the tank is filled with 5–9 mm graded layer of coal to a depth of 10 cm. The top of the coal layer is covered with a fine plastic net (<0.5 mm mesh) to avoid intermixing of sand and coal. Graded layers of gravel and sand, as described in
Table 1, are laid over this plastic net. A garden soil 18 cm deep is laid over a plastic net which separates the soil layer from the sand. The plastic net restricts the movement of earthworms into deeper layers of sand and gravel. The earthworms (*Eisenia fetida*) were introduced into the soil and were allowed to acclimatize. In order to distribute the feed wastewater uniformly a drip arrangement was made.

**Operation of the system**

The various units in the treatment system were arranged in such a way that a gravity flow was maintained through the system. The SGF and ACW were operated in upflow and downflow modes, respectively. The system was operated in sequential batch mode. The steps involved in the operation are described below:

1. Initial trial runs were conducted to relate flow, HRT and extent of outflow valve opening in settling tank. The results of these trial runs were used to mark the valve opening positions for various HRTs to be achieved in the system.
2. The settling tank was filled with wastewater with the outflow valve closed. A settling time of 30 minutes was allowed.
3. The outflow valve of settling tank was opened to the extent required to achieve a specified HRT thereby feeding the SGF at the bottom.
4. The flow from the SGF enters continuously into the ACW at the top and was spread uniformly until the closure of the outflow valve of settling tank. After the stoppage of flow from the settling tank, there is a drawdown of wastewater level in the ACW. During this drawdown period the ACW aeration system comes into action and provides an avenue for external air being sucked into the ACW thereby aerating the entire bed of stone grit.
5. The secondary effluent from ACW was fed uniformly by the drip system to the tertiary system, which works in the downflow mode. The secondary effluent first moves through VF followed by the adsorption unit (coal bed). The tertiary effluent was collected in a closed container.
6. Steps 2 to 5 were repeated for each of the batches. The organic loading was varied and each of the organic loading for a specified HRT constituted a batch.
7. The required amount of settled feed wastewater was collected for analysis. The flows from SGF, ACW and VF

<table>
<thead>
<tr>
<th>Material</th>
<th>Size</th>
<th>Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>8–16 mm</td>
<td>15</td>
</tr>
<tr>
<td>Gravel</td>
<td>5–2 mm</td>
<td>15</td>
</tr>
<tr>
<td>Sand</td>
<td>2,000 μ</td>
<td>10</td>
</tr>
<tr>
<td>Sand</td>
<td>400–600 μ</td>
<td>10</td>
</tr>
</tbody>
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Figure 1 | Schematic sketch of hybrid natural treatment system.
were collected through the sampling ports in the respective units on a daily basis and analysed.

**Planning of experiments**

The experiments were planned in two phases: initial and established. The initial phase was the period when the vegetation grew to a certain height and roots developed. In this phase, groundwater was used as feed water for the growth of vegetation.

The established phase was when vegetation had grown to a sufficient height so that it could sustain and treat the wastewater. In this phase, the treatment system was evaluated for its performance in treating the raw wastewater. The feed wastewater was collected daily from a location in the urban locality where fresh sewage flows in an open drain. The organic loading was varied and the performance was assessed in terms of organic matter (biochemical oxygen demand; BOD$_5$). The organic loading was calculated for each of the units (SGF, ACW and VF) separately. The experiments were planned for organic loading in the range 20–110 kg/ha d and HRT between 1 and 3 d. pH was determined to detect the effect within the system. The procedures to analyse these parameters were according to *Standard Methods* (APHA 1998). pH and turbidity were determined by electrometric and nephelometric methods respectively. BOD$_5$ at 20°C was determined by using BOD$_5$ sensor system.

**RESULTS AND DISCUSSION**

**Initial phase**

The initial phase of experimentation covered the growth of vegetation (*T. latifolia*), development of roots and maturation of the system. The freshwater was fed to the system and the growth of plants was observed. The average height of the plants was 40 cm at the end of initial phase. Four weeks was required for adequate growth of the vegetation. The dissolved oxygen (DO) was also determined at various stages of treatment. It was found that the increase in DO was in the range 33–52% during the initial phase of treatment. The increase in DO was observed in both the ACW and VF.

**Established phase**

In the established phase, the treatment system was fed with varied organic loadings and the system was operated at various HRTs. The performance evaluation of each of the treatment units and system as a whole is described below.

**Sand-gravel filter**

The performance of SGF was evaluated for the removal of turbidity and organic matter.

**Turbidity**

The turbidity of feed (settled wastewater) was in the range 20–50 NTU. The turbidity of effluent from the SGF was observed to be less than 1 NTU for HRT of 1, 2 and 3 d. No clogging and ponding effects were observed during the period of study. The turbidity removal mechanism involved was basically mechanical straining.

**BOD$_5$**

Figure 2 shows the variations of BOD$_5$ in influent and effluent of 1, 2 and 3 d HRT with organic loading in the SGF. The BOD$_5$ removal efficiency was found to be in the range 5–25%, 10–30% and 20–40% for 1, 2 and 3 d HRT respectively. The results show that the variation in organic loading does not affect the BOD$_5$ removal rate significantly. The attached and suspended growth microbes are involved in removing soluble portion of BOD$_5$ from wastewater. The basic mechanisms for the removal of organic matter involved attachment of bacteria, growth of biofilm, adsorption of organic matter, decomposition in biofilm and decomposition in voids. A portion of the sand was extracted from the SGF bed and checked for the presence of biofilm. A thin slimy layer was observed around the extracted sand particles. The lesser thickness of biofilm is useful in maintaining aerobic conditions in the SGF. However, detailed microbiological studies of this biofilm were not carried out.
Figure 2 | Variation of BOD removal with organic loading in SGF.

Figure 3 | Variation of pH with varied organic loading in ACW.

Figure 4 | Variation of pH with varied organic loading in VF.
ACW and vermi filter

The performance of the ACW and VF was evaluated for the removal of organic matter and the variation in pH was monitored.

pH

Figures 3 and 4 show the variation of pH with organic loading in the ACW and VF respectively. It can be seen that there is a slight decrease in the pH value in the effluents.

Figure 5 | Variation of BOD and its removal with organic loading in ACW: (a) 1 d HRT; (b) 2 d HRT; (c) 3 d HRT.
Figure 6 | Variation of BOD and its removal with organic loading in VF: (a) 1 d HRT; (b) 2 d HRT; (c) 3 d HRT.
compared to the respective influents. The decrease in pH was observed to be increasing with increase in HRT. The pH of effluents varied in the range 7.10–7.65 during the period of study. The observed pH range was conducive for the bacterial activity.

**BOD₅**

Figures 5 and 6 show the variation of BOD₅ and its removal from ACW and VF with organic loading for HRT of 1, 2 and 3 d respectively. The organic loading in the figure refers to the organic loading on the ACW and VF computed separately. It can be seen that the BOD₅ removal increases with increase in HRT. However, the increase is marginal: BOD₅ removal is 30–50%, 35–60%, and 40–70% for 1, 2 and 3 d HRT respectively in both the ACW and VF. The effluent BOD₅ from the ACW was observed to be less than 60 mg/L (1 and 2 d HRT) and 40 mg/L (3 d HRT) for all organic loadings. The effluent BOD₅ from the VF was observed to be less than 30 mg/L (1 d HRT) and 20 mg/L (2 d HRT and 3 d HRT) for all organic loadings. Increase in HRT did not cause significant increase in the BOD₅ removal. However, HRT of 3 d was found to be adequate for reducing BOD₅ to a value less than 20 mg/L. Figure 7 shows overall BOD₅ removal for the treatment system. The overall efficiency of the system for BOD₅ removal was observed to be 40–60% (1 d HRT), 60–80% (2 d HRT) and 80–90% (3 d HRT).

The processes contributing to the organic matter removal are combinations of suspended growth and attached growth in the ACW. Aerobic decomposition occurs within the voids of grit medium. Biofilm was developed on the root and grit surfaces. Samples of root and grit were collected from the ACW at the end of the study. It was observed that both root and grit surfaces were coated with a slimy layer. The sources of oxygen supply for aerobic decomposition to occur include release of oxygen at the root surfaces and air movement in the ACW induced by the suction action due to lowering of the wastewater level during sequential batch operation.

Organic matter removal occurs in the VF due to the combined actions of soil, earthworms and coal. BOD₅ is removed from the wastewater by earthworms; the enzymes in the gut of earthworms help in the degradation of several of those chemicals which otherwise cannot be decomposed by microbes. Earthworms intensify the organic loadings of wastewater in the VF soil bed by the fact that they granulate the clay particles thus increasing the ‘hydraulic conductivity’ of the system. They also grind the silt and sand particles thus providing high total specific surface area, which enhances the ability to adsorb the organic and inorganic matter from the wastewater passing through.

The microbes play an important role in a vermi-biofiltration system and they also provide some extracellular enzymes to facilitate rapid degradation by earthworms of organic substances in vermibeds. Earthworms and aerobic microbes act symbiotically to accelerate and enhance the decomposition of organic matter. The soil and small stones of the VF bed and microbial system in the control biofiltration unit are responsible for chemical oxygen demand reduction while in the vermi-biofiltration system enzymes, secreted by earthworm and gut-associated microflora,
reduce those chemicals which otherwise cannot be decomposed by microbes (Suthar 2010). Studies on microbial diversity and structure in vermifiltration were carried out by Wang et al. (2011a, b).

The earthworms were used for the treatment of high organic strength industrial wastewater and domestic waste-water. The results of these studies indicate that survival of earthworms in wastewater is not a major issue provided the worms acclimatize to the conditions within the treatment system, no detrimental effect on earthworms was observed in the present study.

CONCLUSIONS

A pilot-scale hybrid natural system consisting of SGF, ACW and VF with a coal filter for the treatment of domestic wastewater was developed. The developed treatment system was evaluated for its performance by varying organic loading and HRT.

The turbidity of filtrate can be reduced to a value less than 1 NTU by the SGF. The organic loading and HRT (1–3 d) do not affect the BOD₅ removal in the SGF significantly. The contribution by the SGF to BOD₅ removal is 20–30%. The mechanisms involved in BOD₅ removal in the SGF include biofilm development, adsorption and decomposition.

The ACW and VF treatment units of the developed system contribute significantly to increase in DO. ACW and VF contribute equally to the removal of BOD₅ to an extent of 40–60% each and aerobic conditions prevail in both. There is no detrimental effect on earthworm survival and growth due to the feeding of wastewater.

The combination of SGF, ACW and VF performs efficiently for BOD₅ removal. HRT of 3 d for the system is appropriate for reducing BOD₅ to a value less than 20 mg/L for an organic loading up to 110 kgBOD₅/ha d. The effluent can be recycled and re-used for non-potable purposes within a household. The hybrid natural system is useful for the treatment of domestic wastewater at household level. It provides a low-cost, efficient, easily operable/maintainable and least mechanized option for wastewater treatment in a decentralized system.

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