Treatment of a molasses based distillery effluent in a constructed wetland in central India


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Abstract A field-scale 4-celled, horizontal subsurface constructed wetland (CW) was installed to evaluate removal efficiencies of wastewater constituents in an industrial distillery effluent. Total and dissolved solids, NH₄-N, TKN, P and COD were measured. This CW design provides four serial cells with synthetic liners and a river gravel base. The first two unplanted cells provide preliminary treatment. Specific gravel depths and ensuing biofilm growth provides anaerobic treatment in Cell 1 and anaerobic treatment in Cell 2. Cell 3 was planted with Typha latifolia with an inserted layer of brick rubble (for phosphorus removal). Locally grown reed, Phragmites karka was planted in Cell 4. COD was reduced from 8420 mg/l 3000 from Cell 1 to the outlet of Cell 4. Likewise other parameters: total and dissolved solids, ammonium and total nitrogen, and total P, indicated declining trends at the 4-celled CW effluent. This study reveals how high strength distillery wastewater strongly impacts morphology, aeration anatomy in the chiseled plant tissues, reed growth; and composition of the biofilm in the specialized substratum. The reliability of a CW for organic and nutrients reduction, in association with a poorly performing conventional system is discussed. There is an immense potential for appropriately designed constructed wetlands to improve high strength wastewaters in India.

Keywords COD; constructed wetland; distillery effluent; methane; molasses; Phragmites karka; tidal flow system

Introduction

Use of constructed wetlands (CWs) now has been established as a method for treating domestic and low strength industrial wastewaters that are a low cost alternative to conventional systems. Over the past decade, there has been a growing appreciation of the multiple values and functions of constructed wetlands increasingly used for the treatment of a variety of wastewaters (Haberl et al., 1995; Kadlec and Knight, 1996). In India, production of alcohol by fermentation from sugarcane molasses has been used for the disposal problem of molasses. The raw material for production of ethyl alcohol is ‘molasses’ which is the byproduct of the sugarcane industry. In nearly all distilleries, the bath fermentation mode is adopted with about 12–15 litres of spent wash generated per litre of alcohol produced. The untreated distillery effluent (UDE) is a high strength wastewater and can severely affect the environment if not properly treated. The UDE from the distilleries is characterized with a very high organic load with BOD and COD levels in the range of 35000–60000 mg/l and 60000–120000 mg/l, respectively. A routine conventional treatment system reduces the high organic load utilizing anaerobic biological digestion (biomethanation). Distilleries characteristically utilize biomethanation to generate methane (as fuel to compensate for energy needs). This is followed by conventional secondary treatment requiring continued aeration, which is an energy intensive process.

The performance of the conventional effluent treatment plant (ETP) is such that the outfalls of the secondary treatment system still contain high strength effluent quality. The general practice is to transfer the secondary treatment effluent (STE) into several open earthen lagoons for further natural treatment and/or to place on an open field for sun drying. Therefore, the present study was initiated for evaluating treatment performance of STE in a
field scale horizontal subsurface flow (HSF) wetland to investigate removal efficiencies of organics in terms of COD & BOD and N-P. During this study special design considerations for the ‘constructed wetland’ are intended to provide: 1) an additional aeration system in the medium voids filled with influent and 2) insertion of a ‘brick rubble band’ in the gravel bed to enhance phosphorus removal from the distillery influent.

**Molasses scenario**

There are 285 distilleries in India producing 2.7 billion litres of alcohol and generating 40 billion litres of wastewater/vinasse, annually. The raw material for producing ethyl alcohol is the ‘molasses’, which is the byproduct of the sugarcane industry. During the production of sugar, about 0.40–0.45 tones of molasses per tonne of sugar is produced. Molasses production in India has increased from 2.46 million tonnes in 1984–85 to nearly 9.00 million tonnes in 2000 AD (Mall and Kumar, 1979). About 90% of molasses is used for the production of alcohol by fermentation with the remaining 10% used for cattle feed, foundries and manufacture of citric acid. The population equivalent of distillery wastewater based on BOD has been reported to be as high as 6.20 billion and clearly indicates that India’s distillery waste contributes approximately 7 times more organic pollution than the entire Indian population. With little motivation to impose stringent standard on effluent quality, the untreated or partially treated effluents very often find access to surface and ground water courses. Marginal lands in the vicinity of distilleries are commonly sought to spread distillery effluents. The retention of effluents in several open earthen anaerobic lagoons and solar drying ditches are the primary sources for the odor one encounters while passing through a distillery (Joshi, 1999).

**Methods**

**Site descriptions**

The horizontal subsurface flow (HSF) CW was built for the distillery effluent emanating from a private distillery, Associated Alcohols and Breweries Ltd. The facility is located in Khodigram village in the outskirts of Baraha town in Central India. The distillery supports a conventional treatment system (CTS) with a wastewater capacity of 750 m³/day. The distillery factory effluent is treated in two phases i.e. anaerobic digestion, which produces methane, followed by secondary treatment systems (the extended aeration system). The four-celled CW was constructed during June-July 1999 as a demonstration project to treat 10 m³ distillery effluent per day. No earlier attempts have been made in India to apply CW technology for treatment of high strength distillery wastewater effluent. The distillery occupies more than 200 hectares of land. After secondary treatment, the effluent is retained in several shallow open lagoons for approximately two months to undergo natural treatment and air-drying. During this period, the waste is partially irrigated and re-irrigated after plowing on uncropped fields for sun drying. It is partly being used for crop irrigation after mixing with freshwater from the tube wells. The area climate is typically a dry tropical zone characterized with monsoons with annual rainfall amounts up to 800–900 mm. Rainfall occurs mostly (about 95%) in the rainy season i.e. June-September. The summer season’s (March-mid June) day temperatures range between 40–45°C and between 56–62°C and between 56–62°C around the CW gravel beds.

**CW design**

Earlier successful experience with HSF for treating domestic wastewater (Billore et al., 1999) as compared to the free water surface (FWS) initiated the development of the HSF design for the distillery’s high strength wastewater. In tropical climates, suitable year-round temperatures offer favorable conditions to support growth of emergent plants under
an ever-availability of surface water in the gravel medium. A subsurface CW will function as a bioreactor combining the plants and the ensuing biofilm that actively grow in the gravel medium. Specific sizing of the CW as based on BOD (Cooper et al., 1996) was not followed in the present study for sizing formulation. For this design, sizing of the CW is based on a temperate climate (rather than tropical) in which the biological growth and CW treatment performance is inhibited due to the presence of year-round low temperatures. A four-celled rectangular earthen CW (surface area 364.21 m²) with the daily effluent treatment capacity of 10 m³ (approximately 3.64 hectares 1000 m⁻³) was installed on the natural terrain near the distillery end-of-pipe final effluent discharge after secondary treatment (ST). The effluent after ST was regulated to enter into a pretreatment chamber (PC) before entering into the four-celled CW. Figure 1 indicates the design for two parallel CWs; only the upper 4-celled CW was operational in the first phase.

**Pretreatment**
Distillery effluent even after ST contains solids and floating debris. An open three-partitioned pretreatment chamber (size 5.5 × 3.4 × 2.5 m) was constructed to receive a regulated portion of the ST effluent. The bottom of the first compartment of the PC was filled with round gravel (8–12 cm) for half the depth for development of the biofilm and to capture suspended and dissolved solids. The second chamber had a baffle of a half partition wall to allow the transfer of only the supernatant to the third chamber in the PC. The settled sludge was manually removed routinely from the bottom of the first chamber.

**Cell-1**
This cell was designed to provide anaerobic treatment to the influent and to provide greater detention time for better settlement of organics. The cell had a volume of 148.6 m³, medium porosity 45%, water retention of 66.87 m³, and a residence period of 6.6 days (for a daily flow of 10 m³ influent). To prevent clogging and to maintain proper hydraulic conductivity in the gravel medium of the cell for water flow, a ‘desludging’ facility was installed for frequent removal of the periodically settled bottom sludge by suction.

**Figure 1** Design of ‘constructed wetland’ for Barwaha Distillery wastewater
**Cell-2 as a Tidal Flow System (TFS)**

This special system was installed to provide extra aeration (other than that routinely provided by voids in the gravel medium) to water in the voids and for the biofilm in the gravel medium. Besides round gravel (size 2–5 cm) the bed had 6200 inverted porous ‘baked earthen bowls’ (BEB) or ‘earthen lamps’ arranged horizontally in three tiers one above the other in the bottom among the gravel upward to 15 cm (Figure 1). Each BEB had an internal diameter of 0.179 cm with 200 cc of air holding capacity. The porous earthen bowls (depth 6.35 cm) were manufactured manually by kneading local yellow clay, horse-dung and coal ash in the proportion of 4:1:0.5. The hand made bowls are air-dried for three days and baked overnight in a coal-fired furnace. The horse-dung particles after baking resulted in perforation of the earthen wall with fine micro-pores. The cell had a volume of 71.99 m³, medium porosity 40%, water retention capacity 28.7 m³, and a residence period of 3 days (for a daily influent flow of 10 m³).

For TFS, the plumbing arrangement in the end pipe of the cell has been designed to siphon all the wastewater from cell-2 into cell-3, as soon as the water level reaches just below the gravel surface in the former. The completely drained water allows the gravel bed voids to fill with the air completely including air pockets in the 6200 BEB. The influent flow takes three days to completely fill cell-2 until again it siphons into cell-3 in a 12-hour period. This phenomenon has also been reported as ‘tidal flow reed beds’ (TFRB), a new system gaining attention in recent years (Sun et al., 1999).

**Cell-3 and Cell-4**

Ninety rhizome pieces from *Typha latifolia* (cattail) plants were sown in cell-3 on 20 September 1999, at equidistance. These rhizomes were obtained from 6-year old floating tussocks of cattail in the wetland garden of the Botany department, Vikram University. The cell (gravel depth 0.75 m, volume 63.52 m³, bed porosity 40%, water retention capacity 25.41 m³, water residence time 2.5 days, influent flow 10 m³ day⁻¹) had a wide strip of brick pieces across the width (size 0.6 m × 12.1 m) to adsorb phosphorus in the influent. Cell-4 supports *Phragmites karka* sown on 19 August 1999 (3 months old nursery raised 138 plants) in two-layered gravel medium (cell volume 59.27 m³, porosity, ca 40%, water retention capacity 23.7 m³, wastewater residence time in the bed 2.3 days). The unplanted cell-1 and cell-2 were meant to receive the initial impact of the high strength distillery influent, and were perhaps unable to support the growth of reeds. In contrast, cell-3 and cell-4 with a plant cover and rhizospheric biofilm ensured higher biological treatment to inflowing distillery wastewaters.

**Start up and monitoring**

CWs typically require a few months for vegetation and biofilm establishment and sizeable time for the development of litter and standing dead compartments (Billore et al., 1999). High strength distillery wastewater presents an environmental challenge locally as associated with the liquid waste effluent, gaseous emissions and solid waste. Initially the newly sown plants were irrigated with a dilution of ground water extracted from bore-wells on the distillery campus and the distillery final effluent (1:3 effluent: ground water) from Dec 99 onward at a constant inflow of 10 m³ day⁻¹ distributed to the four-celled CW. During this initial period being of diluted effluent, the reed and cattail plants were enabled to establish slowly through their rhizomatous growth. The outflow of all four cells and diluted pretreatment samples from the CW were collected and analyzed monthly from Dec 99 onward for TSS, TDS, BOD, COD, DO, TKN, NH₄, NO₃N, Total P, pH, Temperature, Conductivity and Salinity.
Results and discussion
The CW system has been in operation and monitoring since Dec 99. Each cell contains inflow and out-flow structures required to provide even distribution of water, reduction in channelization, and specific treatment of pollutants, case by case. The bottom of each cell is sealed initially by yellow clay (Billore et al., 2000), overlaid with a LDP synthetic liner, one percent slope, and sufficient freeboard to contain stormwater during the rainy season, and to protect the tall reed and cattail plants from strong winds. The CW gravel media was from the nearby flowing perennial River Narmada. This gravel is round and smooth and of the finest quality for full development of a biofilm. Except for color removal, the treatment performance of the 4-celled CW has been showing promise, initially by treatment of the major wastewater pollutants. A total of 14.4 days was regulated as the retention period when pretreated effluent enters cell-1 until it leaves as effluent from cell-4 for renovation.

Plant growth: Reed and cattail
In fact, the distillery effluent (spent wash) has a highly polluting nature containing almost all the characteristics of original molasses except the fermentable sugar. Establishment of a successful ‘root zone’ system in the gravel bed was a crucial ‘acid test’ in the application of CW technology for treating high strength distillery effluents. Of highest importance is the survival of reed and cattail plants under the influence of the strong organic loading, solids, nitrogen, and soluble salts (sulphates, chlorides). Dilution of the distillery effluent was a prerequisite to ensure growth of the reed and cattail plantation in cell-3 and cell-4. The distillery effluent even after the conventional secondary treatment contained a BOD as high as 2539 and a COD Of 13866 mg/l⁻¹. The plant growth responses indicated 7 to 12 times increase in shoot and belowground (roots and rhizomes) biomass in both the planted species of CW when they achieved a growth period from 2 to 5 months. In contrast, the plant morphology of Reed grass initially exhibited the impact of a stressed environment in the habitat due to the influent loading. The length of tiller internodes and of leaves was 3.3 and 4.4 times smaller during the 5-month growth period, as compared to recorded observations at 8 months. Under the stressed environment, the leaves were plentiful in number (188 per tiller) on the grass, but appeared as small green spines (length 5.2 cm) as a rosette on shortened stems (internode length 2.8 cm). However, the stressed morphological indicators disappeared (recorded in the 8 month observations) when new growth in the Reed grass assumed healthy leaves (length 23.1 cm) and higher internode size (length 9.2 cm) in each tiller.

Solids, COD and BOD
The percentage removal of end parameters for solids (TS, TSS, TDS), COD, BOD, nitrogen species, phosphorus, conductivity and salinity parameters from the individual cell of the CW treatment system are presented in Figure 2. Among the solids, dissolved solids were 89% with suspended solids comprising the remaining portion. Decreases in solid concentrations to 6337 mg/l⁻¹ (about 40%) were observed in the outflow from cell-4 with 80% of the removal occurring in the macrophyte planted cell-3 and cell-4 of the CW. Plants seem to constitute a substratum for the fixation of decomposing microorganisms that act as filters for the dissolved organic matter.

Traditionally, organic matter in the wastewater is characterized by COD, BOD and TOC and often divided into a particulate and dissolved fraction. The spent wash contains numerous amounts of dead microbial biomass, besides volatile organic acids due to fermentation (Poggi-Varaldo, 1992). In addition, the byproduct remaining after distillation during the production of alcohol is characterized by a high concentration of organic acids and polyphenols (Lalov et al., 2000). These are the reasons for the relatively high values of the
COD in the liquid distillery effluent. Cell-1 of the CW having a maximum depth is performing as an ‘anaerobic digester’ removing significantly, 44% of the COD for a total removal of 64%. Table 1 reveals the results of preliminary monitoring completed during January 2000 for methane fluxes as an indicator of anaerobic/aerobic in all four cells, clearly indicating highest methane flux, i.e. anaerobic stage in cell-1 (442.16) compared to the relatively aerobic stage in cell-2 (102.26); plant mediated aerobic cell-3 (56.64) and cell-4 (22.08 CH₄ mg m⁻² day⁻¹) respectively, in the CW.

Cell-1 and cell-2 have been left unplanted for full development of a biofilm on the round, smooth-surfaced river gravel. The measurement of the COD as the oxidisable matter in the biofilm is an indirect estimation of the fixed biomass of total biofilm amount (Brayers and Characklis, 1981). Wastewater biofilms are very complex systems consisting of microbial cells and colonies embedded in a polymer matrix whose structure and composition is a function of biofilm stage and environmental condition (Lazarova and Manem, 1995).  

**Nitrogen and phosphorus removals**

The highest removal of organic and ammonium nitrogen which are present in significant amounts in the pretreatment effluent after the dilution, occurred in the unplanted anaerobic cell-1 and cell-2 in the CW. However, ammonium N continues to be removed in subsequent planted cell-3 and cell-4 in a slight lower magnitude (Figure 2). Nitrate nitrogen which is very low in concentration in the pretreatment effluent (11.9 mg/l⁻¹), and initially removed by 38% in the anaerobic cell-1, formed again in cell-2 having the ‘tidal flow system’ and subsequently removed considerably in cell-4 with the reed plantation. Differences in percent removal in nitrogen species can be explained by the residence time in the cell, aerobic-

### Table 1  Preliminary study on methane emission from different cells in the constructed wetland for the treatment of distillery effluent (January 2000)*

<table>
<thead>
<tr>
<th>Cell No.</th>
<th>METHANE FLUX</th>
<th>CH₄ mg/m² h⁻¹</th>
<th>CH₄ mg/m² day⁻¹</th>
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<tr>
<td></td>
<td>Morning</td>
<td>Evening</td>
<td>Average</td>
</tr>
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</tr>
<tr>
<td>4</td>
<td>0.82</td>
<td>1.01</td>
<td>0.96</td>
</tr>
</tbody>
</table>

*measured by close chamber, GC FID column
anaerobic controlled nitrification-denitrification pulse (Reddy et al., 1989), plant uptake, volatilization (Billore et al., 1994), or biofilm immobilization. The surface temperature of the gravel bed in each cell with temperatures reaching 56–62°C during the summer season (March to mid-June) significantly enhances ammonia removal through volatilization. The HSF constructed wetland in the present study was capable of removing 50–60% of the nitrogen species within a short span of time after its operation. This occurred before full development of a biofilm in the unplanted gravel-bed cells and in the reed-bed-rhizospheres of poor cattail and reed covers. For stepwise nitrate nitrogen reduction in each cell through denitrification, the endogenous carbon sources, such as ethanol, acetate and sugars were already in the distillery effluent to affect the removal process (Werner and Kayser, 1991). Methane may also present a possible sole carbon source for denitrification. Methane production during wastewater anaerobic treatment has been assumed to be 0.25 kg CH₄·kg⁻¹·BOD removed (Thalasso et al., 1997).

Cell-2 in the CW has been characterized by special facility of supplementing air into the gravel bed by a ‘tidal flow system’ (TFS), an eco-engineered process that was further improved in the present study by introducing a more porous and diffusive reed bed. Results clearly illustrate an increase in DO (233%) and nitrate concentration (14.20%) in the outflow of cell-2. In the TFS, the bed is alternately filled with water and then drained completely. During the water filling process, the air is expelled and the reed bed matrix is gradually submerged. Once the whole bed is saturated, the water begins to drain. Fresh air is drawn positively from the atmosphere into the bed during the draining process. Thus, the water behaves similarly to the action of the ‘piston’ in an air compressor (Sun et al., 1999). Therefore, the air drawn into the TFS is used to remove the pollutants, enable maximum media-water contact, and the problem of poor water distribution is avoided (Sun et al., 1999). Likewise, the cattail-planted cell-3 has been improved horizontally by inserting a wide strip of ‘brick rubble’ across the gravel medium to remove the phosphorus from the distillery influent by surface adsorption. Figure 2 displays a relatively higher removal of phosphorus (35%) from the ‘brick rubble’ banded cell, compared to cell 2 and 4. This supports the sorptive role of an adsorbent low cost inert substratum besides other removal mechanisms involved (Richardson, 1985; Mann, 1990), thus removing a total of 79% phosphorus from the distillery influent in the CW.

Conclusion
Conventional wastewater treatment technologies are generally based on highly optimized physical, chemical and microbiological processes. Conventional technologies may not offer affordable solutions to a developing country like India for achieving the ultimate “end-of-pipe” purification of wastewater effluents eventually discharged to India’s rivers and streams. The molasses based distillery is an immensely water intensive process. The present study to treat distillery effluent from the conventional secondary treatment, has demonstrated the potential for application of ‘constructed wetland’ technology in association with a poorly performing conventional treatment process. The constructed wetlands also provide eco-friendly treatment alternatives, instead of large unlined lagoons that are built without proper engineering and environmental care for wastewater storage and subsequent groundwater contamination.

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References


