

Chapter 9

Experiences with laboratory and pilot scale constructed wetlands for treatment of sewages and effluents

Dinesh Kumar and Shyam R. Asolekar

9.1 INTRODUCTION

Constructed wetlands (CWs) have been implemented as wastewater treatment facilities in many parts of the world, but to date, the technology has been largely ignored in developing countries in general and Indian sub-continent in particular, where effective, low-cost wastewater treatment strategies are urgently needed (Arceivala & Asolekar, 2006; Asolekar *et al.*, 2013; Chaturvedi *et al.*, 2014). CWs are used extensively to treat domestic (Billore *et al.*, 1999; Kadlec & Knight, 1996) and industrial wastewaters (Hammer, 1989; Billore *et al.*, 2001). They have also been applied to passive treatment of diffuse pollution including mine wastewater drainage (Hammer, 1989; Kadlec & Knight, 1996; Jing *et al.*, 2001), and highway runoff following storm events (McNeill & Olley, 1998). Besides, CWs, being a model ecosystem, can serve as wildlife habitats and can be perceived as natural recreational areas for the local community (Hawke & José, 1996).

Most recently, it has been envisioned that CWs can be applied in place of or in combination with some appropriate post-treatment technologies to provide techno-economically feasible and socially acceptable way for wastewater management (Arceivala & Asolekar, 2012). The reuse, or reclamation, of wastewater using CW technology also provides an opportunity to create or restore valuable wetland habitat for wildlife and environmental enhancement. Kadlec and Knight (1996) have discussed in detail the various advantages of using wetland technology for wastewater treatment. An additional benefit gained by using wetlands for wastewater treatment is the multi-purpose sustainable utilization of the facility for uses such as swamp fisheries, biomass production, seasonal agriculture, water supply, public recreation and wild life conservation. In the appropriate climatic condition of India, CWs could be successfully established with plant species acclimated to the tropical environment and harvested for use in secondary functions like fuel production.

CWs include free water surface, and sub-surface flow systems. Based on the type of flow, sub-surface flow systems are further classified into vertical sub-surface flow constructed wetlands (VSSF-CWs) and horizontal sub-surface flow constructed wetlands (HSSF-CWs). The sub-surface flow systems involve sub-surface flow through a permeable medium. The “root-zone method” and “rock-reed-filter” are other names for these systems that have been used in the literature. Because emergent aquatic vegetation is used in these systems, they depend on the same basic microbiological reactions for treatment. The pollutants in such systems are removed through a combination of physical, chemical and biological processes including sedimentation, precipitation, and adsorption to soil particles, assimilation by the plant tissue, and microbial transformations.

The performance of CW depends on many factors including its type and design, organic loading rate and hydraulic retention time (Karpiscak *et al.*, 1999). In spite of having significant nutrient removal capability, due to the effect of changing temperatures, the treatment efficiency of CWs tends to change throughout the year (Bachand & Horne, 2000; Healy & Cawley, 2002). The macrophytes growing in CWs have several properties in relation to the treatment process that make them an essential component of the design (Brix, 1997). Selection of plant species for treatment of wastewater by CWs always remains a difficulty to scientists working in this area because metabolism of the macrophytes affects the treatment processes

to different extents depending on the type of the CW. The plants species used in CWs designed for wastewater treatment should therefore: (1) be tolerant of high organic and nutrient loadings, (2) have rich below-ground organs (*i.e.* roots and rhizomes) in order to provide substrate for attached bacteria and oxygenation (even very limited) of areas adjacent to roots and rhizomes and (3) have high above-ground biomass for winter insulation in cold and temperate regions and for nutrient removal via harvesting (Koncalova *et al.*, 1996). Vymazal (2011) has reviewed the plants used in HSSF-CWs and concluded that local species which are easily available and grow well under local climatic conditions are most suitable. Among those plants, many ornamental species have been used, especially for on-site treatment where aesthetics is often a part of the design (Vymazal, 2011).

9.1.1 Scope and objectives

The possible ways to improve the efficiency of natural treatment systems (NTSs) in general and engineered CWs in particular comprise of incorporating the most common and the best practices into wastewater treatment plants (WWTPs) at the design-stage itself. Also, a knowledge-based approach will have to be systematically implemented during construction, commissioning as well as operating and maintaining the facility. The research and technology development activity undertaken in Work-Package-3 of the Saph Pani Project were planned and executed with this overall idea. It was also recognised at the outset that the enhancement of the performance of a given WWTP based on the engineered CW-technology can be achieved when the eco-centric technology implemented in the project performs according to the intended functions in the treatment train (Asolekar, 2013). Furthermore, the natural treatment technology based WWTPs will be suitably adopted, operated and maintained by the given community if the treatment train incorporates suitable tertiary treatment to produce recyclable quality of treated sewage. Some of the important factors that should be considered while deciding upon a strategy to improve the treatment efficiency of NTSs include rate, extent and variability of wastewater reaching the system, climate changes, population changes, pattern of urban and industrial development, changes in agricultural practices, soil erosion and sedimentation, scope of construction activities in nearby areas, and nutrient loading.

A multi-pronged experimental and modelling approach was planned and implemented under these areas. Accordingly, the following outcomes, addressing the specific objectives pertaining to enhancement of the performance of engineered CWs are presented in this chapter:

- I. Interventions leading to improvement of treatment efficiency
- II. Enabling strategies for successful operation

9.2 METHODOLOGY

The knowledgebase required for planning, designing, constructing, operating and maintaining of HSSF-CWs has been one of the focuses in the Saph Pani Project. Accordingly, the methodological details pertaining to the studies on media and vegetation as well as the kinetic experiments are presented in the following sub-sections:

1. Studies on media and vegetation
2. Kinetic studies using laboratory CW-reactors
3. Studies in pilot-scale HSSF-CW

In addition, the significance of the above studied parameters has also been elaborated in their respective sections.

9.2.1 Studies on media and vegetation

Since the packing (medium) in CW-bed plays an important role, several media were investigated from a number of materials available locally for study and characterization. The media were subjected to examination of sieve analyses, porosity, bulk density, scanning electron microscopy (SEM analysis) with energy dispersive X-ray spectroscopy (SEM-EDX) and Fourier transform infrared spectroscopy (FTIR) for characterizing the micro-structure and chemical characterization of solid surface. The standard methods and protocols, as outlined by Gee and Bauder (1986), were employed for sample preparation and analyses of the media. The instruments used for characterization of media are listed in Table 9.1.

In order to identify the appropriate species of vegetation for CW-bed, six plant species were selected for characterization in this study, namely: *Canna indica*, *Typha latifolia*, *Colocasia esculenta*, *Sagittaria latifolia*, *Justicia americana* and *Hymenachne amplexicaulis*. The plant samples were collected from their natural habitats (typically natural wetlands or wetlands created due to land disposal of untreated or partially treated wastewater) in the communities surrounding Mumbai – especially the peri-urban suburbs and the adjoining villages. The plant samples were gently washed with tap water to remove

any sticking soils attached to the roots and stems. Further, the plants were air dried at room temperature to evaporate any excess water droplets attached with the biomass.

Table 9.1 The instruments and references for methods used for characterization of media employed in laboratory CW-reactors.

Sr. No.	Description of Sample & Parameter	Sample Preparation	Analytical Method	Equipment
1	Porosity of packed media	Gee and Bauder (1986)	Gee and Bauder (1986)	Measuring cylinder
2	Bulk density of packed media	Gee and Bauder (1986)	Gee and Bauder (1986)	Measuring cylinder
3	SEM-EDX analysis of packed media	Teršič (2011)	SEM-EDX spectrometer	LEO-1530VP
4	FTIR analysis of packed media	KBr technique	FTIR spectrometer	Bruker IFS 66 vs-1 spectrometer

At least five plants were sampled from each pile of plants and subjected to further tests. Each species was separated into roots, stems, leaves and flowers by chopping the plants samples (Figure 9.1). The fractions were weighed to record the wet weight-fractions of the given plant species. Further, the samples were subjected to hot air drying at 101°C and the corresponding dry weight-fractions were also recorded.



Figure 9.1 The whole plants sampled from their natural habitats and further processed and chopped for estimation of dry and wet weight-fractions. (a) Whole *Typha latifolia* plants, (b) Chopped *Typhala tifolia* plants, (c) Whole *Canna indica* plants, (d) Chopped *Canna indica* plants.

9.2.2 Kinetic studies using laboratory CW-reactors

Box-type open crate (of PVC) was used for holding the randomly packed media in the laboratory CW-reactors. The reactors were devised with an outlet flow control valve fitted at the bottom of the crate so that the reactor could be drained without disturbing media. The dimensions of the crate are given in Table 9.2.

Table 9.2 Dimensions of the CW-reactors used in the study.

Dimension	Size
Length (inner edges)	0.605 m
Breadth (inner edges)	0.405 m
Depth	0.235 m (packed bed) and 0.075 m (free board above media)
Plan area (top surface)	0.245 m ²
Bulk volume of the packed bed (solids and pore volume)	0.0576 m ³

The laboratory CW-Reactors, used in this study, was setup and commissioned at the outskirts of IIT Bombay Campus. In case of the unplanted “control” reactor, raw sewage settled in equalization-well at the pumping station was deposited in each reactor (24 L volume) and retained for 24 hours. At the end of this batch process, the sewage was drained completely and fresh sewage was deposited in the laboratory CW-Reactor. This cycle was repeated for 14-days and the media were conditioned. A similar 14-day conditioning routine was implemented in case of the reactors to be planted. At that point, the conditioned laboratory CW-Reactors were planted with *Canna indica* seedlings having the stem lengths of typically 300 to 400 mm. Hereafter, both, the planted as well as un-planted control laboratory CW-Reactors were subjected to similar routine of sewage deposition.

In order to expose the young seedlings in a progressive manner through the sewage, all the laboratory CW-Reactors were first subjected to diluted sewage (50% raw sewage and 50% bore-well water) for a period of 14-days. Subsequently, the laboratory CW-Reactors were subjected to 100% raw sewage settled in equalization-well for a period of 60 days. It was observed that the seedlings planted in the reactors had grown nearly to 600–700 mm height and appeared lush green, luxurious and firmly rooted in the media with healthy growth of rhizomes. The media in, both, the planted as well as un-planted control laboratory CW-Reactors at the end of 90–100 days of conditioning and acclimatization process were found to have rather uniform coating of bio-film and the bed were odor-free and exhibited the typical smell of aerobic packed-bed sewage treatment system (like trickling filter). At this point the laboratory CW-Reactors (control and planted) were subjected to kinetic studies.

The laboratory CW-reactors were placed in a garden open to atmosphere in an area not covered by tree shade. Each batch run was conducted in triplicates in planted CW-reactors as well as one reactor was run analogously without plants (control). Experiments were conducted in batch mode in the laboratory CW-reactors by charging 24 L of raw sewage. The laboratory reactors were setup to receive sewage from the equalization well where the entire IITB Campus wastewater is collected and settled. The laboratory CW-reactors had manufactured sand as the packing material and *Canna indica* (yellow flower variety) as well as the *Canna indica* (red flower variety) were the two plant species experimented with. All the planted reactors including the reactor without plants were filled with 24 L of wastewater (HSSF-CW conditions) and sampled at the beginning of batch run (time $t = 0$) and subsequently at the end of 24, 48 and 72 hour reaction periods. At the time of sampling, the entire water (24 L) contained in the given laboratory CW-reactor was drained using the outlet valve and the sample was collected from the collection bucket after mixing the contents. Afterwards, the contents of bucket were poured back into the reactor to continue degradation.

Typically, the raw sewage had the concentrations of 5-day biochemical oxygen demand (BOD₅) of 80 ± 20 mg/L, chemical oxygen demand (COD) of 180 ± 25 mg/L, total kjeldahl nitrogen (TKN) of 15 ± 5 mg/L, and total phosphorous (TP) of 3 ± 1 mg/L. The initial, intermittent and final samples from the CW-reactors were collected after specified time intervals and analysed for pH, temperature, turbidity, conductivity, BOD₅, COD, TKN, total phosphorous and suspended solids. Sewage samples and treated effluents were tested using the standard methods (APHA *et al.*, 2005). In a given batch experiment, the samples were typically collected after 24, 48 and 72 hour reaction periods and analysed for the above stated parameters. Finally, the removal efficiencies for targeted pollutants in different laboratory CW-reactors were estimated and interpreted in the context of vegetation in the reactors and the associated media. The rate constants were also estimated by interpreting the experimental data to gain insights into the kinetics of reactions that represented removal of pollutants in the HSSF-CW.

9.2.3 Studies in pilot-scale HSSF-CW facility

IIT Bombay has designed, constructed and commissioned a pilot-scale HSSF-CW having dimensions 13m × 3m × 0.6 m for investigating some of the significant issues associated with design, operation and maintenance of engineered CWs. The plant species *Canna indica*, which was selected as one of the suitable plant species based on the laboratory CW-reactor studies, was planted in the pilot CW. The raw sewage from IITB Campus (settled in equalization-well) was fed to the pilot-scale

CW facility. The schematic of the pilot-scale CW-facility is shown in Figure 1.7 of Chapter 1 and the pictures of laboratory CW-reactors as well as pilot scale HSSF-CW are shown in Figure 9.2.



Figure 9.2 Laboratory CW-reactors and pilot-scale CW facility used in the research on IIT Bombay Campus, Mumbai. (a) Laboratory CW-reactors, (b) Pilot-scale HSSF-CW at IIT Bombay Campus.

9.3 RESULTS AND DISCUSSION

Studies were conducted using laboratory CW-reactors operated in batch mode. Also, a pilot-scale HSSF-CW facility was designed, built and commissioned for demonstration and research purposes. Locally available sewage from the campus of IIT Bombay was used as the feed to the wetland. The objectives of this research were to determine suitable plant species to be applied in the wetland, the assessment of performance of the system and to explore innovative ways to utilize the harvested biomass. Some of the salient results from this research have been categorized and reported in the following sub-sections:

- characterization of media and vegetation,
- biodegradation kinetics using laboratory CW-reactors,
- performance assessment using pilot-scale HSSF-CW and
- strategies for performance enhancement.

9.3.1 Characterization of media and vegetation

The physical characteristics of the various wetland bed media were estimated (porosity 45–70%, bulk density 700–1,400 kg/m³). The microstructure and morphology of manufactured sand was characterized with the help of micrographs obtained from SEM, as depicted in Figure 9.3a. The micrograph indicated that the micro-cracks were approximately of 5–10 micrometer width and the attached fine particles were of 1–10 micrometer diameter. The FTIR spectroscopic analysis indicated that silica, calcium, aluminium and iron were the significant elements dominating surface composition as seen in Figure 9.3b. Similarly, the surface morphology and composition of several media including natural sand, quartz sand, manufactured sand etc. were investigated. The manufactured sand, when used as packing medium in laboratory CW-reactor, was found to be effective in removal of phosphorus owing to presence of calcium, iron and aluminium in the surface composition of the mineral present in the rock.

As stated earlier, six plant species from the locally available natural wetlands were identified and sampled for further characterisation. Those plant species (*Canna indica*, *Typha latifolia*, *Colocasia esculenta*, *Sagittaria latifolia*, *Justicia americana* and *Hymenachne amplexicaulis*) were analysed for wet and dry weights. The whole plants were sampled from their natural habitats and further processed, chopped and dried for estimation of the respective weight-fractions (Table 9.3).

It should be noticed that the weight fractions of total biomass above ground and total biomass below ground have the variability among the plant species with respect to their dry weight-fractions (as depicted from the range given). This information plays an important role in the selection of plant species in the context of the pollutants to be addressed as well as the extent of removal to be achieved in the treatment facility. It is well known that on one hand the foliage assists in photosynthesis and thereby production of oxygen (Uzman, 2001). On the other hand, the rhizosphere (the sub-surface volume around roots) supports a healthy and diverse consortium of aerobic microorganisms – which thrives in case of those plant species, which have larger network of roots. It is well known that the overall performance of a given natural wetland or engineered CW depends on synergistic interaction of biotic and abiotic components of the system – especially the media, vegetation and pollutants (Gyssels *et al.*, 2005). The plant roots provide necessary surfaces for attachment of beneficial

microorganisms as well as provide oxygen for their metabolism (Brix, 1994; Reed *et al.*, 1995). The carbonaceous and nitrogenous pollutants in wastewater subjected to the root zone in constructed wetland are thus typically processed (degraded) by microbes and also through plant uptake as well as through interaction with soils.

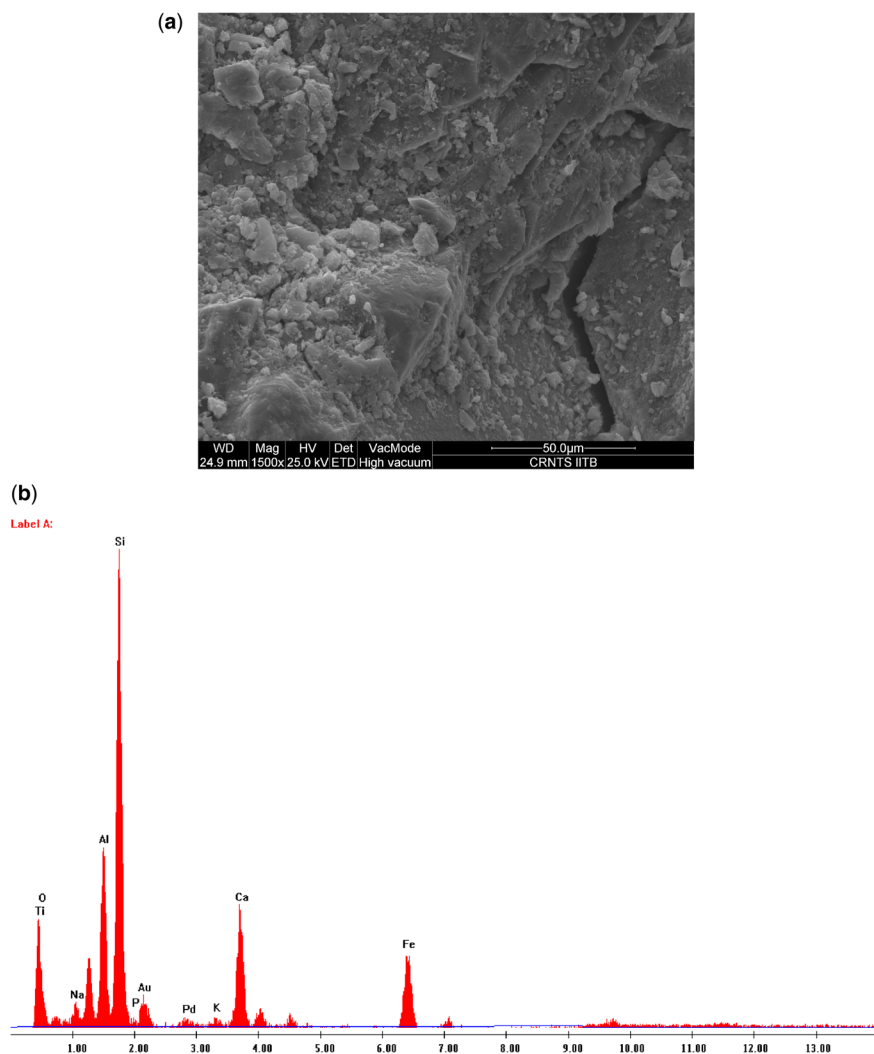


Figure 9.3 Characterization of manufactured sand with the help of (a) image obtained from the scanning electron microscope (SEM) and (b) the Fourier transform infrared (FTIR) spectra indicating chemical composition of mineral surface.

Table 9.3 Comparison of the average range of wet and dry weight-fractions of the six plant species included in this research.

Sr. No.	Plant Part	% Range of Dry Biomass	% Range of Moisture Content
1	Root	9.3–16.5	83.5–90.7
2	Stem	6.2–7.2	92.8–93.8
3	Leaf	7.2–21.6	78.4–92.8
4	Flower	14.4	85.6
5	Total biomass above ground	10.5–16.6	83.4–89.5
6	Total biomass below ground	11.6–16.6	83.4–88.4

9.3.2 Biodegradation kinetics using laboratory CW-reactors

The biodegradation kinetics in CW is conventionally assumed to be of first order and it is used for the design of CWs. Although, the first order model provides a very simple method of designing; it has many limitations in explaining the biodegradation phenomenon especially when the rate constant varies with time. The first order decay model is unable to describe the flow and removal process occurring in the wetland, mainly due to the strong interdependence between the hydraulics and kinetics. To tackle this limitation, Monod kinetics or time-based retardation kinetics for biodegradation is suggested in literature (Rousseau *et al.*, 2004). In Monod kinetics, biodegradation follows a Monod-type equation and in time-based retardation kinetics, the biodegradation rate constant is claimed to vary with time along with temperature.

The three plant species namely: *Canna indica*, *Typha latifolia* and *Phragmites australis* were found to be the most suitable in the Indian context because they are typically found abundantly in “natural wetlands”. Our nation-wide survey (see chapter 8) had reported that those species have also been successfully employed in most of the working CW-based sewage treatment plants across India. Batch experiments were conducted using the laboratory CW-reactors planted with *Canna indica*. Experimental runs were conducted and the data were analysed for assessment of treatment efficiencies and estimation of degradation rate constants. Efficiencies of the reactors were also interpreted in the context of different media used in packed beds. Figure 9.4 presents kinetic data of a set of experiments conducted to study degradation of pollutants using laboratory CW-reactors. Figures 9.4a, 9.4b and 9.4c depict pollutant removal in control (no plants) batch runs, pollutant removal in *Canna indica* (yellow flower) in the batch runs and pollutant removal in *Canna indica* (red flower) in the batch runs.

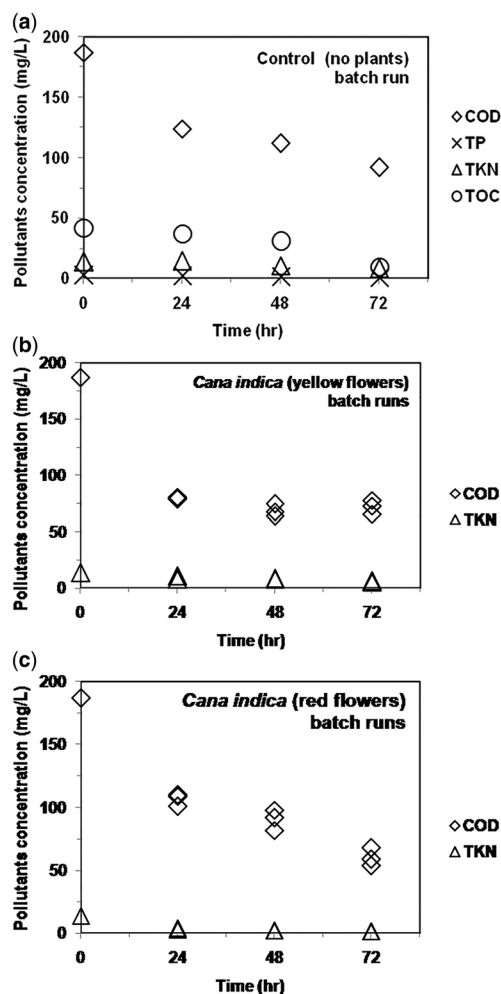


Figure 9.4 Assessment of pollutant degradation kinetics using laboratory CW-reactors. (a) pollutant removal in control (no plants) batch runs, (b) pollutant removal in *Canna indica* (yellow flower) in the batch runs and (b) pollutant removal in *Canna indica* (red flower) in the batch runs.

Percentage removal of COD, TP, TKN and total organic carbon (TOC) in 72 hours of reaction time in batch runs conducted outdoor using laboratory CW-reactors packed with manufactured sand treating sewage from IIT Bombay Campus is depicted in Table 9.4. The control reactor showed lesser %-removal of COD when compared with the %-removal in case of reactors with plants (51% when compared with 61 or 68%). Kumar *et al.* (2015c) hypothesized that the difference between the CW-reactors with and without plants in a way demonstrate the enhancement of COD removal achieved on account of facilitation of photosynthesis-related production of oxygen introduced by the plants in the respective reactors and thereby promoting elevated aerobic degradation in the rhizosphere. In other words, clearly, the shoot of the plants (especially through photosynthesis in the foliage) as well as the root system of the plant (rhizosphere) contribute in enhancement of the performance of CW-reactors with plants. This can roughly be estimated as nearly 10%. Similarly, the results displayed in Table 9.4 showed the plant-mediated enhancement in case of removal of COD, TP, TKN and TOC.

Table 9.4 Percentage removals of COD, TP, TKN and TOC in 72 hours of reaction time in batch runs conducted outdoor using laboratory CW-reactors packed with manufactured sand treating sewage from IIT Bombay Campus.

Description of Reactors	COD Removal	TP Removal	TKN Removal	TOC Removal
Control reactor (without plants)	51%	60%	41%	40%
Reactors with <i>Canna indica</i> (yellow flower)	61% [10% enhancement due to plants]	80% [20% enhancement due to plants]	56% [15% enhancement due to plants]	62% [22% enhancement due to plants]
Reactors with <i>Canna indica</i> (red flower)	68 [17% enhancement due to plants]	89 [29% enhancement due to plants]	90 [49% enhancement due to plants]	80 [80% enhancement due to plants]

It is clear from Table 9.4 that compared to control reactors (without plants) the presence of both plant species enhanced the removal of all the pollutants studied. Furthermore, Table 9.4 also highlights the effects of two different plant species belonging to the similar genus (Kumar *et al.*, 2015c). The *Canna indica* (red flower) species appears to remove more COD, TP, TKN and TOC by about 10%, 11%, 60% and 29%, respectively; when compared with the *Canna indica* (yellow flower) species. Although the magnitude of the numbers need confirmation with the help more experimental data, it can nevertheless be concluded that the performance of laboratory CW-reactors consisting of manufactured sand packed beds planted with *Canna indica* (red flower) species showed noticeable better performance when compared with *Canna indica* (yellow flower) species in nearly all the pollutants.

The kinetic data thus, obtained were also interpreted by Kumar *et al.* (2015c) using the so-called “first-order” kinetics owing to the simplicity of the kinetic model. It was argued by them that in several analogous situations, biological degradation does confirm to the first-order kinetics (even referred to as pseudo-first order kinetics). The first-order rate expression can be represented as:

$$\frac{dC(t)}{dt} = -k \cdot C(t) \quad (9.1)$$

Initial condition: at $t = 0$, $C_{(0)} = C_0$

Solution of this rate expression is:

$$C(t) = C_0 \cdot e^{-k \cdot t} \quad (9.2)$$

By rearranging the above closed-form solution on the initial value problem, one can linearise the above solution as follows to interpret the kinetic data:

$$\ln\left(\frac{C(t)}{C_0}\right) = -k \cdot t \quad (9.3)$$

Thus, if $\ln(C/C_0)$ is plotted against batch reaction time “ t ”, the slop of the linear regression (fitted line) would be k i.e. pseudo-first order rate constant [1/d] for the given pollutant.

$C(t)$ = outlet pollutant concentration, [mg/L]

C_o = inlet pollutant concentration, [mg/L]

k = pseudo first-order reaction rate constant, [1/d]

Based on this first-order kinetic model, Kumar *et al.* (2015c) the experimental data from the laboratory CW-reactors having packed beds of manufactured sand were interpreted and the pseudo first-order reaction rate constant was estimated to be in the range of 0.35/d to 0.55/d (R^2 values for linear regression were in the range 0.60–0.95) corresponding to different species of *Canna indica*.

9.3.3 Performance assessment using pilot-scale HSSF-CW

A pilot-scale constructed wetland at IIT Bombay campus having dimensions $13\text{ m} \times 3\text{ m} \times 0.6\text{ m}$ is made for the study purpose. The media used is the construction debris having porosity of 0.45. The plant species named *Canna indica* was grown fully for six months. The influent wastewater is being fed from sump that receives the campus wastewater. In order to assess the influence of operational parameters, a group of experiments were conducted using the pilot-plant of HSSF-CW. The parameters taken into consideration included: effective reaction time in wetland bed (24–72 hrs), depth of water column (200 cm–600 cm), recirculation of wastewater, dry periods (12 hrs–24 hrs) in-between two consecutive pilot-plant runs. During performance assessment, around 12 cubic meters of wastewater was filled in the system for 600 cm water column in packed bed (maximum water holding capacity of system through packed medium).

As depicted in Figure 9.5a and 9.5b, the values for COD and faecal coliforms, which are indicative of the efficacy of HSSF-CW, were expressed as the ratios of the typical outlet to inlet concentrations in the respective locations. The engineered CWs are apparently relatively more effective in removing the biodegradable organic pollutants in sewages (indicated by COD). However, the systems are not as effective in removal of faecal coliforms – 3 to 4 log-reduction as it was observed for sewage treatment plants (Asolekar, 2013). The NTS (particularly CWs) are also capable of removing pathogenic entities relatively more effectively when compared with the technologies typically employed in the conventional sewage treatment plants (e.g. activated sludge process, trickling filters, extended aeration, sequential bio-reactor etc.).

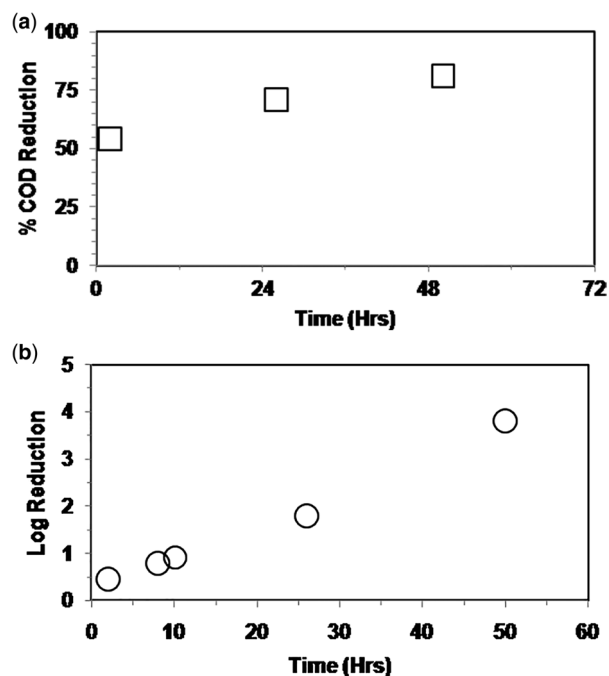


Figure 9.5 Assessment of pollutant degradation using pilot-scale constructed wetland using *Canna indica*. (a) COD removal in batch runs and (b) total coliform log removal batch runs.

Removal of organics and coliform bacteria in pilot-scale HSSF-CW exhibited the so-called pseudo-first order decay kinetics. The pilot-scale constructed wetland was filled with partially settled sewage from sewage collecting well of IIT

Bombay Campus. The raw wastewater represents the actual sewage composition of IIT Bombay Campus and the daily composition found to be quite similar except the seasonal variation. The effective reaction time in wetland bed, depth of saturated zone in the bed, recirculation of wastewater from downstream to upstream position have shown desirable effects and the overall performance of HSSF-CW did improve (Kumar & Asolekar, 2015c). Dry periods (12–24 hrs) in-between the consecutive pilot-plant runs did not seem to influence the removal of coliform bacteria. More experimental work is in progress to investigate the kinetics of degradation and operational issues in this context. The results helped in suggesting measures for improving operational stability, minimising the clogging propensity as well as for determining best practices for operation and maintenance of constructed wetlands.

9.3.4 Strategies for performance enhancement

Inadequate treatment and disposal of sewages as well as the loads brought in by the so-called non-point source pollution emerging from farm runoff and unsewered urban and rural drainages pose the severe challenge of contamination of surface and sub-surface waters in India. The soil aquifer treatment, especially the engineered CWs as well as managed aquifer recharge and riverbank filtration have been concluded to be the useful and relevant candidate technologies having the eco-centric character and competencies for addressing some of the critical problems of aquatic contamination.

Based on the learnings from the research conducted in the Saph Pani Project, the following six-pronged strategy has been proposed:

- 1) Based on the national survey and keeping the significance of NTSs in general and constructed wetlands in particular in mind; it is recommended that the reuse-oriented technological options should be favoured for public investment in the coming future (refer to Chapters 1, 8 and 10 for further details). Such deliberate choices are likely to achieve cost-effective treatment of sewages and thereby will achieve up-gradation of contaminated ambient waters. It has become important that relatively higher quality of waters be made available for the purposes of agriculture, process industry as well as uses in recreation and groundwater replenishment (Kumar & Asolekar, 2015a,b; Kumar *et al.*, 2015b).
- 2) Merely compliance-driven investments are being seen as ecosystem damaging and wasteful. It is concluded in this research that the most appropriate sewage treatment system in India could incorporate excellent primary treatment unit followed by secondary treatment unit based on NTS (Kumar & Asolekar, 2015b; chapter 10).
- 3) Depending on the reuse option prescribed by the community, a high-class tertiary treatment unit followed by disinfection should also be combined with the NTS so that treated wastewater can be gainfully reused (Asolekar *et al.*, 2013; Kumar *et al.*, 2015a; Kumar & Asolekar, 2015b; Chapter 10). The possible ways to improve the efficiency of engineered CWs comprise incorporating the most common and the best practices into WWTPs at the design-stage itself.
- 4) The engineered CW in conjunction with adequate primary treatment and suitable tertiary treatment presents the possibilities of producing treated effluents of rather high quality. Such treated effluents can be used for irrigation, gardening and even for recharging into contaminated urban lakes and ponds (Asolekar *et al.*, 2013; Kumar & Asolekar, 2015b; Chapter 10; present chapter).
- 5) CWs can be applied in place of or in combination with conventionally used wastewater treatment technologies to provide techno-economically feasible and socially acceptable way for wastewater management. The CWs are simple to operate and can be easily combined with cultivation of fodder, production of recyclable water, production of fuel, timber for pulp and paper industry as well as up-gradation of lake or river ecosystem and develop habitats for fishes and birds (Kumar & Asolekar, 2014a; Chapter 8 & 10).
- 6) Strengthening institutional arrangements and financial provisions, which are conducive for incorporating engineered CWs in WWTPs as well as motivating community to own and operate such decentralized systems, is going to be a task to be addressed by the municipalities in the years to come (Starkl *et al.*, 2012; Starkl *et al.*, 2013; Asolekar *et al.*, 2013; Starkl *et al.*, 2015; Kumar & Asolekar, 2015b; Chapter 10).

9.4 CONCLUSIONS AND LESSONS LEARNT

CWs are used to treat domestic and industrial wastewaters world-wide. The engineered CWs are not the isolated example of traditional systems proving to be misfit in the modern times. However, some of the drivers that proved to be favourable to the traditional systems and methods during the yesteryears need to be identified and analysed and efforts should be made to implant those elements into the systems and solutions of the modern times. A knowledge-based approach should

be systematically implemented during construction, commissioning as well as operating and maintaining the CW-facilities. Some of the salient conclusions of this chapter can be summarized as follows:

- The weight fractions have the variability among the plant species with respect to their dry weight-fractions of roots and stems (as depicted from the range given in Table 9.3). The rhizosphere (the sub-surface volume around roots) supports a healthy and diverse consortium of aerobic microorganisms – which thrives in case of those plant species which have larger network of roots (Decamp *et al.*, 1999).
- The three plant species namely: *Canna indica*, *Typha latifolia* and *Phragmites australis* were found to be the most suitable in the Indian context because they are found abundantly in “natural wetlands”. These species have also been successfully employed in most of the working CW-based sewage treatment plants across India.
- The shoot of the plants (especially through photosynthesis in the foliage) as well as the root system of the plant (rhizosphere) contribute in enhancement of the performance of CWs. This can roughly be estimated as nearly 10%.
- The *Canna indica* (red flower) species appears to remove more COD, TP, TKN and TOC by about 10%, 11%, 60% and 29%, respectively; when compared with the *Canna indica* (yellow flower) species.
- Removal of organics and coliform bacteria in pilot-scale HSSF-CW CW exhibited the so-called pseudo-first order decay kinetics.
- The effective reaction time in wetland bed, depth of saturated zone in the bed, recirculation of wastewater from downstream to upstream position have shown desirable effects and the overall performance of HSSF-CW did improve. More details has been given in Kumar *et al.* (2014).
- Dry periods in-between the consecutive pilot-plant runs did not seem to be influencing the removal of coliform bacterial. More experimental work is in progress to investigate the kinetics of degradation and operational issues in this context.

ACKNOWLEDGEMENTS

Authors acknowledge the co-funding obtained from Saph Pani Project by the European Commission (7th Framework Programme) under Grant Number 282911, India as well as from Indian Institute of Technology Bombay for this work.

9.5 REFERENCES

- APHA, AWWA and WEF (2005). Standard Methods for the Examination of Water and Wastewater. 21st edn, American Public Health Association, Washington, D.C.
- Arceivala S. J. and Asolekar S. R. (2006). Wastewater Treatment for Pollution Control and Reuse. 3rd edn, Tata McGraw Hill Education India Pvt. Ltd., New Delhi.
- Arceivala S. J. and Asolekar S. R. (2012). Environmental Studies: A Practitioner's Approach. Tata McGraw Hill Education India Pvt. Ltd., New Delhi.
- Asolekar S. R. (2013). Report on Experiences with Constructed Wetlands and Techno-Economic Evaluation, Deliverable D3.1 SaphPani Project: Enhancement of Natural Water Systems and Treatment Methods for Safe and Sustainable Water Supply in India, Project supported by the European Commission within the Seventh Framework Programme Grant Agreement No. 282911. www.saphpani.eu.
- Asolekar S. R., Kalbar P. P., Chaturvedi M. K. M. and Maillacheruvu K. Y. (2013). Rejuvenation of rivers and lakes in India: Balancing societal priorities with technological possibilities, In: *Comprehensive Water Quality and Purification*, S. Ahuja (ed.), Elsevier, Waltham, United States, pp. 181–229.
- Bachand P. A. M. and Horne A. J. (2000). Denitrification in constructed wetland free-water surface wetlands: II. Effects of vegetation and temperature, *Ecological Engineering*, **14**, 17–32.
- Billore S. K., Singh N., Ram H. K., Shrama J. K., Singh V. P., Nelson R. M. and Das P. (2001). Treatment of molasses based distillery effluent in a constructed wetland in central India. *Water Science and Technology*, **44**(11), 441–448.
- Billore S. K., Singh N., Sharma J. K., Dass P. and Nelson R. M. (1999). Horizontal subsurface flow gravel bed constructed wetland with *Phragmites karka* in Central India. *Water Science and Technology*, **40**(3), 163–171.
- Brix H. (1994). Use of constructed wetlands in water pollution control: Historical development, present status, and future perspectives. *Water Science and Technology*, **30**, 209–223.
- Brix H. (1997). Do macrophytes play a role in constructed treatment wetlands? *Water Science and Technology*, **35**(5), 11–17.
- Chaturvedi M. K. M., Langote S. D., Kumar D. and Asolekar S. R. (2014). Significance and estimation of oxygen mass transfer coefficient in simulated waste stabilization pond. *Ecological Engineering*, **73**, 331–334.
- Decamp O., Warren A. and Sandoz R. (1999). The role of ciliated protozoa in subsurface flow wetlands and their potential as bioindicators. *Water Science and Technology*, **40**, 91–98.
- Gee G. W. and Bauder J. W. (1986). Particle size analysis. In: *Methods of Soil Analysis*. Part 1. Physical and Mineralogical Methods, A. Klute (ed.), 2nd edn, American Society of Agronomy, Madison, United States, pp. 383–411. [http://dx.doi.org/10.1016/S0167-2991\(04\)80157-5](http://dx.doi.org/10.1016/S0167-2991(04)80157-5).

- Gyssels G., Poesen J., Bochet E. and Li, Y. (2005). Impact of plant roots on the resistance of soils to erosion by water: A review. *Progress in Physical Geography*, **29**(2), 189–217.
- Hammer D. A. (1989). *Constructed Wetlands for Wastewater Treatment – Municipal, Industrial and Agricultural*. Lewis Publ., Chelsea, Michigan, United States.
- Hawke C. J. and Jose P. V. (1996). *Reed Bed Management for Commercial and Wildlife Interests (RSPB Management Guides)*, The Royal Society for the Protection of Birds, Sandy, United Kingdom.
- Healy M. G. and Cawley A. M. (2002). The nutrient processing capacity of a constructed wetland in western Ireland. *Journal of Environment Quality*, **31**, 1739–1747.
- Jing S. R., Lin Y. F., Lee D. Y. and Wang T. W. (2001). Using constructed wetland systems to remove solids from highly polluted river water. *Water Science and Technology: Water Supply*, **1**(1), 89–96.
- Kadlec H. R. and Knight R. L. (1996). *Treatment Wetlands*. Lewis, Boca Raton, New York, London, Tokyo.
- Karpiscak M. M., Freitas R. J., Gerba C. P., Sanchez L. R. and Shamir E. (1999). Management of dairy waste in the Sonoran Desert using constructed wetland technology. *Water Science and Technology*, **40**(3), 57–65.
- Koncalova H., Kvet J. and Lukavska J. (1996). Response of *Phragmites australis*, *Glyceria maxima* and *Typha latifolia* to addition of piggery sewage in a flooded sand culture. *Wetlands Ecology and Management*, **4**, 43–50.
- Kumar D. and Asolekar S. R. (2015a). Significance of Engineered Natural Treatment Systems for Treating Sewages: India Case Study. (Manuscript in preparation).
- Kumar D. and Asolekar S. R. (2015b). Integrated Assessment of Natural Treatment Systems. (Manuscript in preparation).
- Kumar D. and Asolekar S. R. (2015c). Pilot-Scale Horizontal Sub-Surface Flow Constructed Wetland to Treat Sewage. (Manuscript in preparation).
- Kumar D., Asolekar S. R. and Sharma S. K. (2015a). Post-Treatment and Reuse of Secondary Treated Effluents using Natural Treatment Systems: The Indian Practices. (Manuscript under review).
- Kumar D., Chaturvedi M. K. M., Sharma S. K. and Asolekar S. R. (2015b). Typologies of Classification of Engineered Natural Treatment Systems in India. (Manuscript in preparation).
- Kumar D., Sutar R. B., Kumar D., Kamble K. A., Reddy B. L. and Asolekar S. R. (2015c). Kinetics of Degradation in Laboratory and Pilot-Scale Engineered Constructed Wetlands Treating Raw Sewage. (Manuscript under preparation).
- McNeill A. and Olley S. (1998). The Effects of Motorway Runoff on Watercourses in South-West Scotland. *J. CIWEM*, **12**, 433–439.
- Reed S. C., Crites R. W. and Middlebrooks E. J. (1995). *Natural Systems for Waste Management and Treatment*. 2nd edn, McGraw Hill Inc., New York.
- Rousseau D. P., Vanrolleghem P. A. and De Pauw, N. (2004). Model-based design of horizontal subsurface flow constructed treatment wetlands: A review. *Water Research*, **38**(6), 1484–1493.
- Starkl M., Brunner N., Amerasinghe P., Mahesh J., Kumar D., Asolekar S. R., Sonkamble S., Ahmed S., Md. Wajihuddin A., Pratyusha S. and Sarah (2015). Stakeholder views, financing and policy implications for reuse of wastewater for irrigation: A case from Hyderabad, India. *Water*, **7**(1), 300–328; doi: 10.3390/w7010300.
- Starkl M., Amerasinghe P., Essl L., Jampani M., Kumar D. and Asolekar S. R. (2012). Potential of Natural Technologies for Decentralised Wastewater Management in India, Decentralised Wastewater Management, International Water Association, November 20–22, 2012, Nagpur, India.
- Starkl M., Amerasinghe P., Essl L., Jampani M., Kumar D. and Asolekar S. R. (2013). Potential of natural treatment technologies for wastewater management in India. *Journal of Water, Sanitation and Hygiene for Development*, **3**(4), 500–511.
- Teršič T. (2011). SEM/EDS analysis of soil and roasting vessels fragments from ancient mercury ore roasting sites at Idrija area. *Geologija*, **54**(1), 31–40.
- Uzman A. (2001). Book review: *Molecular cell biology* (4th edition): Harvey Lodish, Arnold Berk, S. Lawrence Zipursky, Paul Matsudaira, David Baltimore and James Darnell; Freeman & Co., New York, NY, 2000, 1084 pp., ISBN 0–7167–3136–3. In: *Biochemistry and Molecular Biology Education*, **29**(3), 2001, 126–128, ISSN 1470–8175.
- Vymazal J. (2011). Constructed wetlands for wastewater treatment: Five decades of experience. *Environment Science and Technology*, **45**(1), 61–69.