Environmentally Sustainable and Decentralized Municipal Wastewater Treatment Wetlands – An Indian Agricultural Research Institute Experience

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ABSTRACT:
Oxidation pond or activated sludge process are the two most commonly deployed wastewater treatment technologies in India. However, these processes are expensive and require complex operations and maintenance. In view of these limitations, constructed wetland technology has been receiving greater attention in recent years. However, the rate of adoption of wetland technology for wastewater treatment in the developing countries has been low due a general belief that these technologies have large land area requirement. Batch-fed wetland systems with shorter hydraulic retention times (HRTs) have generally been found to translate into smaller land requirement and thus have an implication for their better acceptability in developing countries. Keeping this in view, a batch fed (<1-day HRT) vertical sub surface flow wetland technology based municipal wastewater treatment plant of 1500-LPD capacity was developed at the sewage plot site of the Indian Agricultural Research farm. The pilot plant is in operation since November 2009 and is being continuously monitored for nutrient/ heavy metal (pollutant) mass reduction efficiencies. Long term average pollutant mass reduction efficiency of the pilot system illustrated its capacity to reduce wastewater turbidity and nitrate, phosphate, potassium concentrations by up to 81%, 68%, 48% and 47%, respectively. Planted wetland systems, in general, seemed to be having an edge over the unplanted ones. Nutrient removal efficiencies seemed to be higher for the *Phragmites karka* based wetland systems. The *Typha latifolia* based systems, on the other hand, were observed to be associated with higher oxidation potential and thus higher sulphate reduction efficiencies (50.51%). These systems also seemed to be associated with significantly higher Ni (62%), Fe (45%), Pb (58%), Co (62%) and Cd (50%) removal efficiencies. A comparison of ecological footprint and sustainability of the experimental wetland systems viz-a-viz a hypothetic conventional sewage treatment plant (STP) showed that the experimental wetland systems were 1500 times more sustainable. Based on these experiences, the technology has been recently up-scaled to a 2.2 MLD horizontal sub-surface flow system for treating sewage waters from Krishi Kunj colony, adjoining IARI campus. The up-scaled system has potential to irrigate 132 ha land area of the Indian Agricultural Research farm.

1. BACKGROUND

Freshwater scarcity, generation of increasing volumes of wastewaters, degradation of freshwater resources and the interconnected food insecurity, due to rapid urbanization/ industrialization, is driving many countries to use marginal quality waters in agriculture. Agricultural reuse of wastewater is fast becoming popular worldwide because it closes the loop between water demand and wastewater disposal and enhances fertilizer security of resource poor farmers. However, due to the lack of proper treatment facilities and awareness in developing countries, unplanned application of wastewater/ raw sewage is increasing the risk of agricultural sustainability and consumer/ environmental health. Thus for safe agricultural disposal (with optimum profit); safe, economic and effective treatment of sewage is one of the most challenging problems faced worldwide.

Oxidation pond or activated sludge process are the two most common methods of municipal wastewater treatment in India. These processes are expensive and require complex operations and maintenance. Further, due to improper design, poor maintenance, frequent electricity break downs and/ or lack of technical man power, these conventional wastewater treatment facilities do not function properly and therefore remain closed most of the time. In view of these limitations, in recent years, constructed wetland technology (Mitsch and Gosselink, 2007) has been receiving a greater attention. However, its rate of adoption in the developing countries has been quite low (Denny, 1997); primarily due to a general belief that these technologies have large land area requirement. Wetland systems with shorter hydraulic retention times (HRTs) have generally been found to translate into smaller land area requirement. Further such batch fed systems (with increased detention time) have been reported to be associated with not only lower treatment area (Mehrdadi *et al.*, 2009) but also higher pollutant removal efficiency. This has been observed to have an implication for their better acceptability in developing countries like India. However such batch fed wetland systems, with < 1-day HRT, have not been so far extensively tested across tropical developing countries.

Keeping the aforementioned facts in view a constructed wetland technology based pilot plant was developed at the wastewater irrigated plot site of the Indian Agricultural Research Institute (IARI) farm, with a basic aim to assess its a) pollutant removal efficiency and upscale potential for augmenting IARI-farm irrigation water supplies and b) ecological footprint and sustainability vis-à-vis a conventional sewage water treatment plant.

2. EXPERIMENTAL WASTE WATER TREATMENT SYSTEM

2.1. Design

The experimental wastewater treatment system (Figure 1) of 1500-LPD capacity is in operation since 2009 and comprises of 16 – small scale batch fed (<1-day HRT) vertical sub surface flow (VSSF) experimental wetlands (each of 100 lpd capacity. Each wetland/ mesocosm measures 0.89m (height) x 0.906 m (dia.) and has a surface area of approximately 0.645 m$^{2.}$ These are stratified with fine gravel, coarse sand and native (sandy loam) soil to obtain an effective pore space of 36.5% and a theoretic hydraulic retention time (HRT) of 8.46 ± 3.12 hrs. These mesocosms are planted with 4 replicates of 3 emergent wetland vegetations (e.g., Reed Grass (*Phragmites* sp.), *Acorus calamus* (Vachh) and *Typha latifolia*), 4 replicates of non-vegetated mesocosms and are arranged in a completely randomized (CRD) design.

Figure 1. Components of a 1500 LPD vertical sub-surface flow (pilot) sewage treatment plant

2.2. Influent/ Effluent Water Sampling and Analysis

In order to assess relative nutrient and trace metal removal efficiency of wetlands (with/ without different wetland vegetation types), regular influent and effluent (monthly-composite) water samples were collected during each year, since 2010. The pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), oxidation-reduction potential (ORP), salinity and temperature of the influent and effluent water samples were determined in-situ by means of a HORIBA U-51 probe. While for the remaining chemical analysis, the water samples were collected in two (500 ml and 100 ml capacity) high density polyethylene bottles and immediately transferred to the laboratory where they were stored in a refrigerator at 4^0C until further processing/ analysis. The water samples collected in the 100 ml capacity plastic bottles were immediately acidified with 1 N HNO_3 and subjected to heavy metal analysis while those collected in 500 ml capacity plastic bottles were subjected to the remaining physico-chemical tests.

To determine heavy metal (viz., Cu, Fe, Mn, Zn, Cr, Ni, Cd, Co, Pb) concentrations, the water samples were first acid digested, using di-acid mixture (nitric acid, HNO3: perchloric acid, HClO4 :: 9:4). Fe, Mn and Zn concentrations were estimated through an atomic absorption spectrometer (ECIL AAS4141 model) while those of Ni, Cd, Cu, Cr, Co, and Pb was determined by means of a Polarographic TraceLab Analyzer (POL150 model; Wang, 1989). Turbidity of influent/effluent waters was analyzed by means of a turbidimeter (Hach-2100P-Turbidimeter) while carbonates, bicarbonates, chloride, calcium and magnesium concentrations (meq/L) of influent/effluent water samples were determined through titration method (Jackson, 1973). Sodium and potassium concentrations in the influent/ effluent water samples were determined by means of a flame photometer (Elico CL-361); following Jackson (1973) protocol and fluoride, nitrate (NO_3, ppm) and sulphate concentrations (SO_4, ppm) were estimated as per the procedures illustrated in Clesceri et al. (1998). Phosphate concentrations (PO_4, ppm) were also determined. These were obtained through an amino acid method by means of a UV-VIS spectrophotometer (Hach DR-5000). All samples were analyzed in triplicate with due quality control ensured through careful standardization, procedural blank measurements and duplicate samples.

2.3. Pollutant Mass Reduction Efficiency and Hydraulic Retention Time

The nutrient and heavy metal removal efficiencies (as %) were estimated as per eq. 1:

$$\text{Influent Mass Reduction (\%)} = \{[(C_{in,avg}*\Sigma V_{in}) - (C_{out,avg}*\Sigma V_{out})]/ (C_{in}*\Sigma V_{in})\}*100 \quad (1)$$

where, $C_{in,avg}$ is average influent concentration (mg/L), $C_{out,avg}$ is average effluent concentration (mg/L), ΣV_{in} is total flow volume into the wetland and ΣV_{out} is total flow volume out of the wetland, during the study period.

While the hydraulic retention time (HRT) for each cell of the wetland system, t (in days), was calculated as (eq. 2, Reed *et al*., 1995):

$$t = V/ Q = Ayp / Q \quad (2)$$

where, V (m^3) is the cell volume; A (m^2) is the mean surface area of the cell; y (m) is the flow depth and p (fraction) is the porosity, which expresses the space available for the water to flow through the media, roots and other solids in each cell. The actual average flow rate, i.e. Q (m^3/d), through the porous media in each of the wetland cells/ mesocosms was expressed as per the applicable Darcy's law and eq. (3):

$$Q = K_s A S \quad (3)$$

where, K_s (m/d) is the average hydraulic conductivity of a unit area of the medium perpendicular to the flow direction (expressed as eq. 4) and S (m/m) is the hydraulic gradient of the water surface in the flow system (expressed as eq. 5). The hydraulic conductivity of the porous media in a treatment cell was obtained through the falling head method (Hillel, 1980; eq. 4).

$$K_s = [L/(T_2-T_1)] * Ln [(h_1+L)/ (h_2+L)] \quad (4) \text{ and}$$

$$S = [\text{depth of water above media} + \text{media depth}] / \text{media depth} \quad (5)$$

where, h_1 and h_2 (m) is the depth of water above media at time T_1 and T_2 (d) and L (m) is the total height of the media column (0.70 m).

For this, the mesocosms were first completely drained off. Thereafter these were filled with sewage water up to a maximum depth of 16.51 cm (6.5 inches), above the media and the water was allowed to flow through the media, without maintaining a constant head. The falling water depths above media were recorded at hourly time steps, until these reduced to zero level. Simultaneously, total volume of treated effluent waters produced (until zero effluent discharge) was also determined through volume-calibrated buckets.

2.5. Ecological Footprint and Sustainability

2.5.1. Emergy Analysis

Emergy analysis, a comprehensive environmental accounting technique (Odum, 1996), was applied for comparing the ecological footprint and sustainability of the proposed vertical sub-surface flow wetland system and a hypothetic sewage treatment plant. It uses the thermodynamic basis of all forms of energy, materials and human services, and converts them into equivalents of one form of energy. Hence this approach presents a basic value measure based on emergy as embodied energy, in terms of solar energy used up directly and indirectly to make a product or service, rather than the conventional receiver value-based measure of willingness to pay. Total emergy of an item can be expressed as eq. (6):

$$\text{Emergy (sej)} = \text{available energy of item (J)} \times \text{solar transformity (sej/J)} \quad (6)$$

Where, solar transformity is a measure of how much one type of available energy of an item is worth in terms of the solar energy.

For emergy accounting, firstly the emergy diagram for the sewage treatment plant was sketched to describe the system boundaries, input sources and the converting processes leading to the desired product (i.e. the treated wastewaters). In wetland based systems, the inputs comprise of both renewable (viz., sunlight, rain, wind, native soil, sand, gravel, vegetation and local wastewaters) and (purchased) non-renewable resources (i.e. F_n, including cost of construction, electricity and maintenance). The resources, like sunlight, rain, wind, soil, and wastewaters were regarded as free local renewable resource (R) and sand, gravel, and vegetation were regarded as purchased renewable resource (F_r). In conventional sewage treatment plants (STP), besides local wastewaters and activated sludge, only sunlight and rain that contribute highest annual emergy input to earth were included in the local renewable resource category (R). The rest of the inputs required for the structure development and the mechanical/ electrical operation of the STP were grouped under the purchased non-renewable resource (F_n) category. This was followed by the computation of total amount of annual solar emergy (sej) used to generate the final output (i.e. the treated wastewater) as a product of the total resource utilized (in joules, grams or dollars) and its solar transformity (expressed as sej per unit joule or grams or dollar; eq. 6). The resource-solar transformities were obtained from standard look-up tables available from other studies. While actual resource used (in terms of joules/yr, grams/yr or dollars/yr) was computed as per the standard equations, for the experimental wetland system and a hypothetic STP.

Sustainability of the two wastewater treatment systems, as a function of yield, renewability, and load on the environment, was also evaluated in terms of the four sustainability indices viz., Emergy Yield Ratio (EYR), Environmental Load Ratio (ELR), Emergy Sustainability Index (ESI) and Percent Renewable Index (Pr), as per the following equations:

$$EYR = Y / F \quad (7)$$

$$ELR = [F + N]/R \quad (8)$$

$$ESI = EYR/ELR \quad (9)$$

$$P_r = [R + F_r]/U \qquad (10)$$

where, Y is emergy yield (Y), F is purchased emergy ($F = F_r + F_n$), N is non-renewable indigenous emergy, R is local renewable emergy and U is the total resource use.

2.5.2. Comparison with a Conventional Sewage Treatment Plant

To compare the ecologic footprint and sustainability of the operational experimental wetland system (of approximately 1-KL treatment capacity) with a conventional sewage treatment plant (STP), a hypothetic STP of comparable treatment capacity and an activated sludge type was conceptualized. The components and cost estimates for the hypothetic STP were prepared by the Central Public Works Department Division of the IARI, after detailed site surveys and discussions. The conventional STP included primary treatment with screens, grit chambers and oil traps for removal of large particles and oil, followed by the pre-sedimentation/ chemical induced precipitation and the biological nitrification/ organic matter stabilization in aeration tanks, filtration (through activated carbon filters) and end-sedimentation/ sludge removal and re-circulation through clarifier and sludge re-circulation pumps. The overall treatment efficiency of the hypothetic plant, keeping in view the treatment efficiencies of the various STPs actually operational around different class-I and class-II cities of India, was assumed to be around 50% while the total volume of sludge generation from such a system was estimated through the following eq. (11):

$$\text{Sludge Volume (L/d)} = [BOD*Q*\rho_{sludge}] / \text{Total Solids (\%)} \qquad (11)$$

Where, Q is plant capacity (in 1000L/d); ρ_{sludge} is density of sludge (i.e. 1-kg/L) and total solids at the bottom of the clarifier were assumed as 1%.

3. RESULT AND DISCUSSION

3.1. System Performance

Pollutant mass reduction efficiency for the aforementioned wetland systems (with or without any wetland vegetation) revealed highest turbidity removal efficiency (80.77%) for the unplanted systems, associated with largest hydraulic retention time (53.67 hrs). *Acorus calamus* based wetland systems, with lowest HRT (14.41 hrs), were observed to be associated with lowest turbidity removal efficiency. While *Phragmites* and *Typha* based systems with moderate HRT (14 to 17 hrs) were associated with intermediate (73-76%) turbidity removal efficiency.

Emergent macrophyte based systems, particularly those planted with *Phragmites karka*, seemed to be having an edge over the unplanted systems (with naturally occurring filamentous algae) particularly in terms of nitrate (68%), phosphate (48%) and potassium (47%) removal efficiencies (Fig. 2a-c). While *Typha latifolia* based systems, associated with highest oxidation potential, were associated with the highest sulphate reduction efficiencies (50.51%, Fig. 2d). In general, *Typha* based systems seemed to be associated with significantly higher removal efficiencies with respect to the key pollutants, i.e. Ni (62%) and Pb (58%, Fig. 2e,f) present in the test area wastewaters.

3.2. Ecological Footprint and Sustainability

Emergy accounts for the experimental wetland system and the conventional sewage treatment plant (STP) are presented in Tables 1 and 2. In both the systems, amongst all renewable resources, the largest emergy contribution (99%) came out to be from the wastewater itself thereby re-asserting the fact that “wastewater” is a potentially valuable renewable resource and a high value by-product of the human population. In both the systems, renewable resources such as rain, wind, and sunlight contributed a small emergy input (<1%).

In experimental wetland system, the renewable resources constituted 54.24% of the total emergy used, with the other half (i.e. 45.76 %) contributed by the purchased non-renewable resources such as construction, electricity and maintenance (Table 1). In the renewable (i.e. local + purchased) resource category, the local (i.e. free) renewable resources contributed the maximum (77.69 %) emergy.

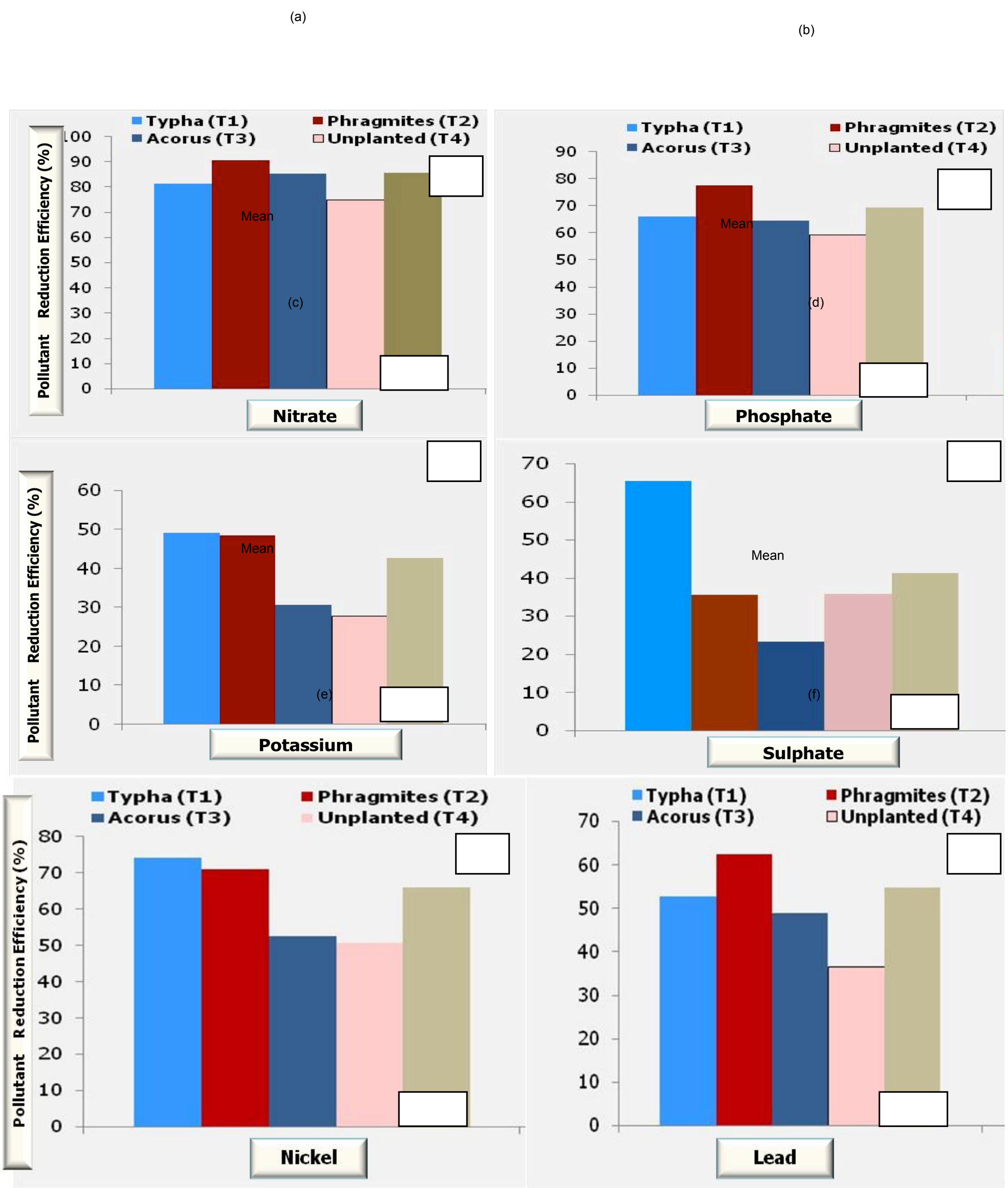

Figure 2. System pollutant reduction efficiency

Purchased renewable resources such as, gravel, sand and vegetation which require service to access constituted only 12% of the total emergy used in the experimental wetland system and were thus the minor source of total system emergy use. Amongst the purchased non-renewable resource category, the labour intensive purchased services such as the construction (63.26%, with an assumed life span of 20 years) and the annual maintenance (36.47 %) contributed the maximum while the electricity contributed the minimum (0.27 %).

In contrast, a comparable (hypothetic) sewage treatment plant was observed to be associated with far higher (98.26%) purchased non-renewable resource emergy use (Table 2). The contribution of total solar emergy used by the non-renewable resources in a conventional STP was about 83 times more than that in a comparable wetland system. Amongst the purchased non-renewable resources, the operational costs such as the maintenance (48.10 %) and electricity (28.31 %) contributed the maximum (76.41 %) with the rest 23.59 % contributed by the construction (with an assumed life span of 20 years). The operational costs for running a conventional STP were observed to be about 173 times higher than that for a comparable wetland system. Further, though construction cost for a conventional STP appeared to be a small fraction (23.59 %) of the total non-renewable resource used yet it was found to be about 31 times higher than that for a comparable wetland system

Table 1. Emergy budget of experimental wetland system

Item	Value (/yr)	Solar emergy (sej / yr)	Emergy value (in $)	Emergy value (in Rs.)
***Local renewable resources* (R)**				
Sunlight	8.73×10^9 J	8.73×10^9	0.001	0.034
Rain, chemical	5.14×10^7 J	2.41×10^{11}	0.021	0.925
Wind, kinetic	4.11×10^5 J	1.01×10^9	0.000086	0.004
Soil	9.20×10^7 g	6.80×10^{12}	0.586	26.083
Wastewater	2.99×10^9 J	1.14×10^{16}	982	43,694
***Purchased renewable resources* (F_r)**				
Gravel	2.51×10^5 g	2.51×10^{14}	21.633	962.25
Sand	3.13×10^5 g	3.14×10^{14}	27.041	1,202.80
Vegetation	2.33×10^2 $	2.71×10^{15}	233.617	10,391.30
***Purchased nonrenewable resources* (F_n)**				
Cost of construction	6.75×10^2 $	7.83×10^{15}	675.154	30,030.88
Electricity	2.09×10^8 J	3.32×10^{13}	2.869	127.61
Maintenance	2.74×10^3 $	3.19×10^{16}	2747	17,314.51
***Total emergy in treated wastewater* (Y)**				
Treated water	1.90×10^9 J	1.10×10^{16}	950	42,270.11
Total emergy inputs		5.44×10^{16}	4690	10,3750.47
Net emergy inputs		4.34×10^{16}	3740	61,480.36

Table 2. Emergy budget of comparable conventional sewage treatment plant

Item	Raw data (/yr)	Solar emergy (sej/yr)	Emergy value (in $)	Emergy value (in Rs.)
***Local renewable resources* (R)**				
Sunlight	1.55×10^{13} J	1.55×10^{13}	1.335	59,388
Total energy in rain	1.05×10^{10} J	1.92×10^{14}	16	737
Wastewater	4.71×10^9 J	1.79×10^{16}	1541	68,582
Activated sludge energy	1.65×10^9	1.22×10^{14}	10	468
***Purchased nonrenewable resources* (F_n)**				
Cost of construction	2.09×10^4 $	2.43×10^{17}	20946	9,31,715
Electrical & Mechanical System	2.51×10^4 J	2.92×10^{17}	25138	11,18,150
Maintenance	4.27×10^4 $	4.96×10^{17}	42715	19,00,000
***Total emergy in treated wastewater* (Y)**				
Treated water	1.91×10^9 J	1.10×10^{16}	950	42,270
Total emergy inputs		1.05×10^{18}	90371	40,19,712
Net emergy inputs		1.03×10^{18}	89420	39,774,42

Sustainability of the two wastewater treatment systems, as a function of yield, renewability, and load on the environment, was also evaluated (Table 3) in terms of the four sustainability indices viz., Emergy Yield Ratio, Environmental Load Ratio, Emergy Sustainability Index and Percent Renewable Index. The analysis showed that the wetland technology based system could exploit local purchased (renewable/ non-renewable) resources far more efficiently than a conventional STP. Further the environmental stress of such a sewage treatment system was 31 times lesser than that a comparable conventional sewage treatment plant. The experimental wetland systems were observed to be utilizing 27 times more renewable resource than a conventional sewage treatment plant and were thus observed to be 1500 times more sustainable than a conventional STP.

Table 3. Emergy Indices for an experimental wetland system and a conventional STP

Emergy Indices	Experimental Wetland System	Conventional STP
Emergy Yield Ratio	0.70	0.01
Environment Loading Ratio	1.37	42.19
Renewable Percentage	0.54	0.02
Emergy Sustainability Index	0.51	0.00034

Figure 3. Components of a 2.2 MLD horizontal sub-surface flow sewage treatment plant

4. OUTCOME

The pilot system could prove to be a viable option for treating municipal wastewaters in peri-urban/ rural areas and was thus up-scaled to a 2.2 MLD horizontal sub-surface flow system for treating sewage from the Krishi Kunj Colony adjoining IARI campus (Fig. 3). Spread over 1.42 hectares, the up-scaled system consists of three treatment cells (Fig. 3a), with HRT of 2.2 days. Each treatment cell is stratified with 60 cm thick layer of stratified gravel, on which *Typha latifolia*- a wetland vegetation - is planted (Fig. 3b). The average pollutant removal efficiency of the 4 months (Nov. to Feb., 2013) old system is quite significant. While biological oxygen demand (BOD) of the influent at the inlet is about 460 milligrams per liter (mg/l), the BOD of effluent is 100 or less at the outlet. Besides this, the system is capable of reducing total suspended solids (TSS) from 220 mg/l to about 2.2 mg/l and nutrients / heavy metals (such as NO_3, PO_4, K, Pb, Fe and Cr) by 75-85%. The treated water is collected in a 4800 m^3 holding tank, from where it is pumped through a riser pipe to the IARI - fields. The so treated sewage water has a potential to irrigate 132 ha of IARI farm lands.

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