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Constructed wetland for improved wastewater management and increased water use efficiency in resource scarce SAT villages: a case study from Kothapally village, in India

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ABSTRACT
Evaluation a field-scale of constructed wetland (CW) for the treatment of rural wastewater (WW), in resource-scarce semi-arid tropic (SAT) villages, to provide improved wastewater management and increased water use efficiency, was the main objective of this study. A CW was commissioned in Kothapally village of Telangana to treat the wastewater generated from 100 households. The CW was vegetated with *Typha latifolia* and *Canna indica*. Average COD, sulfate and inorganic nitrogen removal efficiencies observed were 65%, 60% and 67% respectively, for the study period (one year). Removal efficiency for total coliform was consistently above 80%. The treated wastewater was stored in a farm pond and was utilized for irrigation in the nearby agricultural fields (0.6 ha). This perennial source of water, helped the nearby farmers to cultivate two additional crops, chickpea during *rabi* and sweetcorn during summer. The assured availability of water reduced their vulnerability to dry spells during the *kharif* by providing means for lifesaving irrigation. The biomass harvested from the constructed wetland was used as fodder for the livestock. A net additional income of Rs.70,000 (∼US$1,000) was realized by the farmers using the treated wastewater for cultivation. Similar constructed wetland-based wastewater management system can be scaled up across water scarce semi-arid tropics.

Novelty statement
Field-scale performance evaluation of constructed wetland based wastewater treatment in a semi-arid tropic village is scarce in the literature. The work presented gives a feasibility assessment for this technology critical for its wide-scale application to augment rural wastewater management in resource poor villages.

KEYWORDS
Constructed wetland; decentralized wastewater treatment; phytoremediation; subsurface flow

Introduction

In the year 2015, the estimated surplus sewage volume in India was 38,791 million liters per day (MLD), *i.e.*, 62% of the total sewage generated (CPCB 2016). It is estimated that rural households in India generate 15 to 18 billion liters of liquid waste per day, however, wastewater management remains an alien concept in rural India. Even in villages with cemented drainage network, wastewater drains invariably leads to a wastewater sump at their tail end. These wastewater sumps, ubiquitous in rural India, become notorious for odor nuisance and pose a health-risk of pest/vector diseases to those residing in their vicinity. In developing countries, as much as 80% of illnesses are linked to poor quality water and poor wastewater management. An estimated 842,000 deaths could have been prevented with access to safe drinking water, hand-washing facility and sanitation (The United Nations World Water Development Report 2017). Raw wastewater discharge leads to contamination of surface water bodies and groundwater aquifers (Corcoran *et al.* 2010). Conventional wastewater treatment technologies, being chemical, skill and energy intensive, have thus far not achieved penetration in rural India (Kaur *et al.* 2012). Low-cost technologies such as constructed wetland (CW) utilize the phytoremediation capacity of specific plant species, in combination with physical screening and sedimentation of suspended solids (Machado *et al.* 2017). The aerenchyma tissue (Vymazal 2001), present in macrophytes such as *Typha latifolia* and *Canna indica*, facilitate the transfer of atmospheric oxygen to the root zones, thus creating an ideal micro-environment for nitrification activities (Vergeles *et al.* 2015). Studies have shown that the plant uptake contributes to about 5–15% of the total nutrient removal from the wastewater while the bulk of removal of pollutants takes place in the rhizosphere by the root zone microorganisms (Becerra-Castro *et al.* 2012). Thus, CW offers a sustainable technological solution to augment wastewater management capacities as well as water use efficiency of rural communities (Kelvin and Tole 2011). Despite the known potential of CWs illustrated by researchers their

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studies involving their field-scale application are limited (Khan *et al.* 2020). Laboratory scale experiments with synthetic wastewater (Miguel-Espinosa *et al.* 2020) and artificial light sources, are important to understand the physicochemical processes (Upadhyay *et al.* 2016) and their effect on wastewater treatment efficiency in a CW. However, field-scale implementation of CWs (Leto *et al.* 2013), are needed to instill confidence in the minds of policy makers about their reliability in actual field condition (Huang *et al.* 2016). The present study demonstrated consistent wastewater treatment efficiency by a field-scale subsurface flow CW located in semi-arid tropic village, Kothapally, in Telangana, India. The CW vegetated with *Typha latifolia* and *Canna indica* showed COD, sulfate and inorganic nitrogen removal efficiencies of 65%, 60% and 67%, respectively, for the one year study period. Removal efficiency observed for total coliform was consistently above 80%. The treated wastewater served as a perennial source of irrigation water for the agricultural fields in its vicinity and reduced their vulnerability to unpredictable dry spells during the *kharif* (0.6 ha). Such an assured source of irrigation helped the local farmers to cultivate two additional crops, chickpea during *rabi* and sweetcorn during summer. The biomass harvested from the constructed wetland was used as fodder for the livestock. A net additional income of Rs.70,000 (∼US$1,000) was realized by the farmers using the treated wastewater for cultivation. Similar constructed wetland based wastewater management system can be scaled up across water scarce semi-arid tropics.

Materials and methods

Site selection

Kothapally (17o12′8.93″ N, 78o6′23.5″ E) is a progressive Indian village in the Ranga Reddy district of Telangana state. Growing water scarcity, unpredictable and inadequate rainfall made, rainfed agriculture-dependent livelihoods in Kothapally vulnerable. Integrated watershed development interventions such as rainwater harvesting (Garg *et al.* 2012), *in situ* moisture conservation, soil health rejuvenation, introduction of improved crop varieties and soil micronutrient enrichment have been successfully implemented in Kothapally over the last decade (Karlberg *et al.* 2015). Increasing water use efficiency through water recycling and reuse is critical for the livelihood of villagers. The concept of CW was introduced through village level meetings, stressing the need for proper wastewater management. Both the potential as well as limitations of the technology were highlighted during these meetings to the local villagers to foster pragmatic planning and expectations. Scientific evaluation of the drainage map and topography formed the basis of site-selection, however, enabling the participation of villagers in the decision-making process helped to inculcate a sense of ownership among the villagers about the activity. The wastewater sump located at the tail end of the main drain was a perennial source of foul smell and potential source pest/vector diseases in the village. The main village drain carrying wastewater from 100 households (population 497) was identified for the activity and the public land near the wastewater sump at its tail end was utilized for the wastewater treatment unit. Wastewater from the drains of individual households drained through PVC pipes to the cemented (Supplementary Figure S1) drain canals (mostly covered). Thus the percolation and evaporation loss were both negligible. It is worth mentioning that villagers suggested a site about 30 m further downstream of their existing wastewater sump, although it meant incurring additional cost toward putting a 30 m long cemented pipeline (Supplementary Figure S2), such flexibilities are critical for the successful implementation of the project. The implementation team and their strategy must not be oblivious to common 'not in my back yard' tendency seen for wastewater treatment units. Bar screens were put at the inlet of the pipeline to prevent floating materials and plastics from clogging the pipeline.

Constructed wetland

The constructed wetland was designed for a flow of 20 m^3/day which is the volume of water supplied to these households from a village overhead tank to community taps. It is worth noting that the area near the community tap sees a lot of bathing and washing activity. Individual household wastewater discharge drained through PVC pipes (Supplementary Figure S1) to the main drain pipeline. The pipe underground drainage line (Supplementary Figure S2) means very negligible percolation or evaporation loss. The subsurface horizontal flow type CW used in this study consisted of a brick-masonry structure (20 m × 4 m × 1.5 m) with plain cement concrete lining at the bottom. The total cost of construction for this unit was $9895. The bed porosity was found to be 0.53 by falling-head tests. The pore volume was computed to be 63.6 m^3. Thus the hydraulic retention time was approximately 3 days. Peak flow periods were observed between 5 am and 7 am on a typical day. The general layout and the details of its filter media are given in Figure 1. The filter bed of the CW was constituted of three horizontally stratified layers (each 30 cm thick) of aggregates (40 mm aggregates at the bottom, 20 mm aggregates in the middle and 10 mm aggregates at the top) covered with a 15 cm thick layer of coarse sand (1.5 mm). To prevent loss of sand in the event of high flow following a significant rainfall event the top sand layer was guarded by 0.15 mm baffle (a single brick layer) placed on the top of the 10 mm gravel layer on both the inlet as well as the outlet side. Gravity flow of wastewater was ensured by providing a bed slope of 1% (Metcalf and Eddy. Inc. 1991). The inlet wastewater drain was connected to the 40 mm aggregate layer and the wastewater flow direction in the CW was bottom-up type (Figure 1). The wastewater was allowed to enter from the bottom of the CW at the inlet side and exit from the top of the 10-mm gravel layer at the outlet side. Wetland was vegetated with *Typha latifolia* saplings and *Canna indica* suckers on 20 May 2015 (Supplementary Figure S3). The plant species were placed at 30 cm spacing. We selected these two species based on our in-house

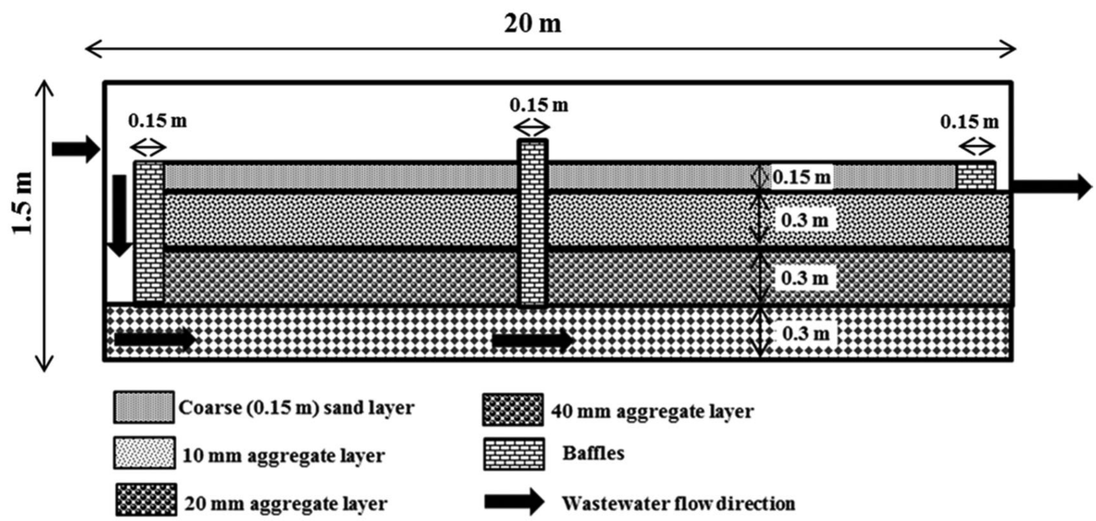

Figure 1. Schematic of the constructed wetland commissioned in Kothapally, Telangana (Double-column fitting image).

detailed research where we compared the suitability of several species (Tilak *et al.* 2017). The main advantages of both these species are, first, their high growth rate and consistent phytoremediation capacity without much seasonal variation; second, they do not harbor harmful pests or insects and thirdly, both species do not spread beyond the designed vegetated area and do not pose the threat of becoming a 'new weed'. The planting material was collected from the existing constructed wetland in ICRISAT (Supplementary Figure S3), Patancheru campus (Datta *et al.* 2016). Both *Typha latifolia* and *Canna indica* covered 40 m^2 area each in the CW, where the former covered 10 m of the length from the inlet side and preceded the *Canna indica* vegetation which covered the remaining 10 m length of the CW bed. The treated wastewater from the CW was stored in a pond (dimension of 20 m × 4 m × 2.5 m) located downstream of the CW. The water storage capacity of the pond was 200 m^3 (~10 days treated wastewater volume). The pond had stone-pitched side-walls with a compacted clay liner at the bottom. The various phases of construction are depicted in Figure 2. The pond had stone-pitched side-walls with a compacted clay liner at the bottom. The overflow from the pond was connected to the existing stream toward the downstream direction. Maintenance of constructed wetland requires the skill of a gardener for routine activities such as harvesting and cleaning the rubbish.

Wastewater sampling and analysis

Live monitoring of water quality using real-time monitoring tools and data-loggers was not possible mainly due to two reasons, first, it generally restricts the number of parameters we can monitor reliably; second, the risk of theft of such an expensive instrument at a roadside village location. Bi-weekly wastewater samples (1 L each) were collected manually in wide-mouth high-density poly-ethylene (HDPE) bottles (Tarsons, product code: 584250) in triplicates from the inlet and outlet of the constructed wetland. The bottles were transported in cold boxes to the ICRISAT Patancheru campus within 2–3 h of sampling for analysis of various parameters during the period of July 2015 to July 2016. Standard methods (Supplementary Table S1) of wastewater analysis (APHA 2005) were adopted for different physical and chemical parameters (Datta *et al.* 2016). The pathogen removal efficiency of the CW was measured in-terms of *Escherichia coli* using the most probable number (MPN) method by adopting standard procedures (Kaushal *et al.* 2016). Further details about the analytical procedure adopted may be found in the Supplementary Material.

Top layer sand sampling

Monthly sampling of sand was carried out during the study period. A sand auger (AIC Agro Instruments Pvt. Ltd, India), was used for sand sampling (at depths of 0–5 cm). Sand samples (each of 100 g) were collected in triplicate from both the *Typha latifolia* vegetated area as well as *Canna indica* vegetated area and subsequently one (100 g) composite samples were prepared for each area.

Plant biomass sampling

The above-ground biomass was harvested manually using hedge smears at 45 days interval. The fresh weight was recorded using a spring balance immediately after harvesting (Supplementary Figure S4). Composite plant samples (5 kg for each macrophyte) were collected from the harvested biomass for analysis. The plant samples were kept in 5 kg muslin bags. The plant samples (or sweet corn) were dried in an oven at 65 °C for 48 h.

Sand and plant sample analysis

The sand samples were air-dried and ground to get a uniform grain size of 2 mm. Analysis of both sand and plant samples were carried out in the Charles Renard Analytical Laboratory (CRAL) at ICRISAT, Patancheru. The total nitrogen was analyzed adopting the thio-sulfate modification of the Kjeldahl method to include nitrate and nitrite

Figure 2. Different phases of construction of the constructed wetland; bed preparation (A), compaction (B), masonry work (C), introduction of concrete liner (D), completion of plastering and curing (E), filling-up of the filter media constituents (F), plantation (G), stabilization (H).

(Sahrawat *et al.* 2002a). The plant samples (or sweet corn) were dried in an oven at 65 °C for 48 h. The dried plant (or sweet corn) samples were then ground using an industrial-grade grinder (Willey, Nebraska, USA) to a fine powder. Total nitrogen in plant materials was determined by digesting the samples with sulfuric acid-selenium. Nitrogen in the digests was analyzed using an auto-analyzer (Skalar SAN System, AA Breda, Netherlands) (Sahrawat *et al.* 2002b). The concentrations of trace metals in the plant samples as well as in the samples were determined by

Table 1. Average inlet wastewater characteristic (July 2015–July 2016).

Sl. No.	Parameters	Inlet
1	Arsenic (μg L^{-1})	1.1
2	Bio-chemical oxygen demand (mg L^{-1})	187.7
3	Boron (mg L^{-1})	0.155
4	Calcium (mg L^{-1})	142.8
5	Chlorides (mg L−1)	297.19
6	Chemical oxygen demand (mg L^{-1})	240
7	Detergents (mgL^{-1})	9.21
8	Electrical conductivity (dS m^{-1})	1.85
9	Fluorides (mg L^{-1})	1.32
10	Magnesium (mg L^{-1})	83.83
11	Ammoniacal-nitrogen (mg L^{-1})	34.60
12	Nitrate-nitrogen (mg L^{-1})	5.4
13	pH	7.42
14	Phosphates (mg L^{-1})	0.7
15	Potassium (mg L^{-1})	17.44
16	Sodium (mg L^{-1})	182.42
17	Sulfate (mg L^{-1})	61.2
18	Sulfur (mg L^{-1})	19.7
19	Total alkalinity (mg L^{-1} as $CaCO_3$)	342
20	Total dissolved solids or TDS (mg L^{-1})	1,903
21	Total hardness (mg L^{-1} as $CaCO_3$)	1,100
22	Total suspended solids or TSS (mg L^{-1})	52
23	Total coliform (mL^{-1})	1,700

Cadmium, chromium, cobalt, copper, nickel, manganese, iron and zinc were consistently below detectable limit of ICP-Mass Spectra analysis.

inductively coupled plasma emission spectrophotometer (ICP-AES) (Prodigy High Dispersion ICP, Teledyne Leeman Labs, Hudson, New Hampshire, USA) in the digests prepared by digesting the samples with nitric acid.

Design of the constructed wetland

The wastewater flow in the village drain to the constructed wetland was estimated from the water supplied to the households connected to the inlet drain (Supplementary Figure S1). The overhead tank, which supplies water to these households, receives 20 m^3/day. Assuming 70% of the supplied water gets converted into wastewater, the design flow for CW was 14 m^3/day with 2.73 days hydraulic retention time (HRT). After the installation of the cemented pipeline, direct flow measurements were conducted using plastic drums of 1,000 L capacity (Ramprasad and Philip 2016) during the construction phase (1 March 2015 to 1 April 2015) on multiple occasions throughout the day. Initial measurements found that 85% of the wastewater flow comes between 6.00 h and 18.00 h during a day with the peak flow periods between 6.00 h and 11.00 h. The average daily flow computed was between 10 and 12 m^3/day which implies an actual HRT of approximately 3 days (excluding the evaporation and evapotranspiration loss within the constructed wetland).

Results and discussion

Characteristics of the wastewater

The average wastewater characteristics during the study period are given in Table 1. The irrigation guidelines prescribed by the Central Pollution Control Board (CPCB, India) classifies irrigation water quality as Class E. Water quality for Class E requires pH of 6.0–8.5, electrical conductivity (EC) of less than 2.25 dS/m, sodium absorption ratio (SAR) less than 26 and boron concentration of less than 2 mg/L (CPCB 2020). The effluent from the constructed wetland was within these set permissible limits throughout the study period. The wastewater characteristics did not show much seasonal variation except during the monsoon season. Storm-water incursion and diluted influent wastewater post rainfall events, particularly for a rainfall of more than 5 mm. However, the study period being a drought-hit period such days were very few. An increase in the concentration of total suspended solids was observed during the monsoon period (Supplementary Figure S6). The COD concentration in the influent wastewater was near about 250 mg/L, lower values were recorded though following rainfall events (Supplementary Figure S7). Inlet concentration of sulfate varied between 50 mg/L and 70 mg/L, the transition period between *kharif* and *rabi* showed values closer to 50 mg/L whereas the period of enhanced agricultural activity showed values closer to 70 mg/L. A low value of 17 mg/L was observed during the winter (Supplementary Figure S8). Incursion of agricultural run-off may be the reason behind variation observed in sulfur concentration, as ammonium sulfate was one of the main inorganic fertilizers applied by the nearby farmers. The salt concentration as well as physical parameters such as pH and electrical conductivity (EC) remained steady with minimal variation (5–7%) during the study period. The wastewater was devoid of any heavy-metals during the entire study period, only on one occasion trace level (0.01 mg/L) of arsenic was detected in the wastewater. The absence of heavy metal highlights the irrigation potential of rural wastewater. The high biochemical oxygen demand (BOD_5) to COD ratio (0.78) highlighted higher amenability of the wastewater to biodegradation. The phosphorous (Supplementary Figure S8), ammoniacal-nitrogen (Supplementary Figure S9) and nitrate-nitrogen (Supplementary Figure S10) concentrations of the wastewater reflect its eutrophication potential. Utilization of the treated wastewater, thus, not only provides a perineal source for fertigation but also increases nutrient use efficiency prevents environmental degradation by recycling of the nutrients such as nitrogen, phosphorous and sulfur back to soil. The high ammoniacal-nitrogen to nitrate-nitrogen concentration ratio may be attributed to the shorter and mostly covered travel path for the wastewater from individual households to the constructed wetland. The average total coliform content observed in the influent of the pathogen was about 1,700/mL highlighting the health risk of raw wastewater irrigation both for the producer and consumer of the produce, however, it showed considerable variation.

Performance of the CW

Two distinct phases of operation were observed in the constructed wetland, the steady state phase was preceded by a brief stabilization phase. The stabilization phase started with plantation of *Canna indica* and *Typha latifolia*, and lasted for 40 days (20 May 2015 to 30 June 2016). Wastewater samples were collected for analysis from the inlet as well as the

Table 2. Average inlet and outlet concentration and removal efficiencies for different key wastewater parameters in the constructed wetland (July 2015–July 2016).

	Inlet concentration (mg L^{-1})	Outlet concentration (mg L^{-1})	Removal efficiency (%ge)
TSS	52 ± 18.3	7.2 ± 2.1	86.15
Sulfate	61.2 ± 11.0	24.53 ± 4	59.92
COD	240 ± 27.6	92.3 ± 11.4	61.54
Phosphate	0.7 ± 0.2	0.32 ± 0.1	54.29
Ammoniacal-Nitrogen	34.66 ± 5	14.37 ± 2	58.54
Nitrate-Nitrogen	5.4 ± 0.8	1.22 ± 0.4	77.41
Total coliform	1,700 ± 202.9	124 ± 16.1	92.7

outlet of the CW every week during this period. Significant variation between inlet and outlet concentrations was observed for few key parameters such as total suspended solids (TSS), sulfate, chemical oxygen demand (COD), phosphate, ammoniacal-nitrogen and nitrate-nitrogen (Table 2). These were identified as performance indicators for the constructed wetland. The removal efficiency was calculated from the average inlet and average outlet concentrations of the wastewater samples collected during this period. During the stabilization phase, the CW showed high (94–98%) TSS removal efficiency. Physical screening and sedimentation may be the reason for the high removal efficiency of 98% observed for TSS during the stabilization phase (Kaushal *et al.* 2016). As the macrophytes got established, marked increase in COD and inorganic nitrogen removal was observed. The removal efficiencies eventually got stabilized toward the end of this 40 days stabilization phase. The establishment of rhizosphere zone microorganisms has been identified as critical for CW performance (Jizheng *et al.* 2012). As the plants grow the surface area of plant roots increase, which aid, the growth of rhizosphere zone microbial biofilm which in turn augments biodegradation of pollutants present in the wastewater in the root zone. Both *Typha latifolia* and *Canna indica* possess aerenchyma (Cooper *et al.* 1996), and thus, can facilitate oxygen transport to its rhizosphere. Such availability of oxygen as the terminal electron acceptor promotes the growth of nitrifiers. Furthermore, the availability of nitrate-nitrogen near the root zone in turn induces the growth of denitrifiers (Vymazal 2011). The period from 1 July 2015 to 1 July 2016, was the post-stabilization phase where the performance of the CW was evaluated. Overall removal efficiency was calculated from the average inlet and average outlet concentrations observed over the study period. The removal efficiencies for different key wastewater parameters post stabilization phase are presented in Table 2. The root zone micro-organisms utilize the available organic carbon during nitrification–denitrification process and thus play a critical role in the removal of BOD in constructed wetland (Xing 2012). The overall COD removal efficiency was between 65% and 72% consistently post stabilization phase of the CW. Leto *et al.* (2013) in their study with subsurface flow CW treating first-flush stormwater in Sicily (Italy), have reported a COD removal efficiency of 65–69% and a total nitrogen removal efficiency of 60–66%. No significant seasonal variation in the COD, inorganic nitrogen or sulfur removal efficiency was observed during the study period (Table 2). An increase in the inorganic nitrogen removal was observed after each harvesting event which may be attributed to an increased plant uptake. In fact, with plant height a drop in the inorganic nitrogen removal helped to identify the optimized harvesting period for both the plant species. The optimum harvesting period for *Typha latifolia* was found to be 41 days where for *Canna indica* it was 45 days. For the sake of simplicity in maintenance activity, harvesting was carried after every 45 days for both the plant species which required the engagement of two human labors for a day. After harvesting, fresh weight was taken for the plant biomass and plant samples were collected for analysis of tissue concentrations. The removal efficiency for inorganic nitrogen showed an increase of 3–5% during the first two weeks after harvesting probably owing to the rapid plant regrowth post harvesting. However, overall, the influence of plant growth phase on removal efficiency for COD, sulfur or other parameters were moderate. This highlights the dominant role of root zone microorganisms, compared to plant nutrient uptake, on the overall wastewater treatment efficiency in the CW. The average phosphate removal efficiency observed over the study period is 54.29% where the inlet concentration varied between 0 and 0.9 mg/L. Previous researchers have reported that subsurface flow horizontal CWs have a higher potential for phosphate removal as the substrate is constantly flooded and there is not much fluctuation in redox potential in the bed materials (Vymazal 2001). However, in the absence of adsorption based entrapment, common in peat or soil-based media, plant root uptake becomes the main removal mechanism for phosphate in CWs with inert media such as granite aggregates (Vymazal 2007). It is important to highlight here that although organic carbon-rich plant litter may aid in the removal of sulfate in a constructed wetland, periodic harvesting of plant biomass is important to achieve net nutrient removal as nutrients stored by the aboveground plant biomass of macrophytes gets released during their decomposition. It is worth mentioning that even before the horizontal-subsurface flow CW was vegetated with *Typha latifolia* or *Canna indica*, the average removal efficiency was 68% and 72% for total and fecal coliforms, respectively, through abiotic removal processes. However, the presence of macrophytes increased the removal efficiency for Total coliform as reported by previous researchers (Stefanakis *et al.* 2014). The CW showed consistently high removal efficiency for fecal as well as total coliform and the average removal efficiency were 87% and 92%, respectively. High removal efficiency of more than 90% is common in constructed wetlands for examples García-Ávila *et al.* (2019) reported removal efficiency of more than 98% for a vertical subsurface flow constructed wetland vegetated with *Phragmites australis* and *Cyperus papyrus* treating municipal wastewater

Table 3. Average plant tissue concentrations of *Typha latifolia* and *Canna indica*.

Plant species	Total N (mg/kg)	Total P (mg/kg)	Total K (mg/kg)	Sulfur (mg/kg)	Fe (mg/kg)	Zn (mg/kg)	Ca (mg/kg)	Mg (mg/kg)
Typha latifolia	22,534 ± 179	3,911 ± 80	26,924 ± 164	7,158 ± 135	506 ± 59	15 ± 1.2	11,032 ± 78	4,625 ± 82
Canna indica	22,974 ± 186	4,394 ± 108	42,343 ± 185	2,169 ± 144	703 ± 72	13 ± 1.2	8,597 ± 404	6,362 ± 171

in the city of Santa Isabel, Ecuador. Removal efficiency greater than 90% was reported for *Escherichia coli* by Leto *et al.* (2013) in their study with *Arundo donax* L. and *Cyperus alternifolius* L. vegetated horizontal subsurface flow constructed wetland treating pretreated urban wastewater in Sicily (Italy). Coliform contamination levels of above 103/mL affects the quality of vegetable crops like radish and lettuce (Blumenthal *et al.* 2001). The relatively stable outlet wastewater characteristics, irrespective of seasonal variation or human interventions such as harvesting clearly demonstrates the reliability and consistency of the CW performance as a decentralized wastewater treatment technology. Unlike wastewater generated from urban and peri-urban areas, the absence of heavy metal in the wastewater samples, throughout the study period, highlights the safe irrigation potential of wastewater generated from this type of semi-arid villages. The salt removal efficiency observed in the CW was negligible and the average sodium adsorption ratios (SAR) for the inlet and outlet wastewater were 2.9 and 2.7, respectively.

Removal of fecal coliform at high pH environment of the storage tank

Post-treatment the residual nitrogen and phosphate concentration in the treated wastewater triggered algal growth in the storage pond in the abundance of sun-light (Vymazal 2011). The growth of algae resulted in a rise of pH with an average value of 8.5 (Vymazal 2007). Total removal of fecal coliforms was achieved in the storage tank as a consequence of pH. Fernández *et al.* (1992) explained the presence of flora influences through several factors such as competition, predation, etc. to facilitate the removal of fecal coliform in an algal pond and not the pH rise alone. Increase in pH takes place due to CO_2 consumption by the algae; nutrient competition, production of toxins and addition of oxygen by the algal biomass enhances fecal coliform die-off rates. Adhesion/attachment to the algal cells also eliminates coliforms.

Although several processes such as ammonia volatilization, nitrification, denitrification, nitrogen fixation, ammonification, nitrate-ammonification, anaerobic ammonia oxidation (ANAMMOX) and adsorption affect the removal of nitrogen in a constructed wetland, most processes just convert nitrogen to its various forms (Vymazal 2007). The phytoremediation ability of rooted macrophytes such as *Typha latifolia* and *Canna indica* is closely linked to their great nutrient uptake capacity which accounts for their greater productivity in comparison with planktonic algae in many systems (Wetzel 2001). Nitrogen assimilation refers to the biological processes which convert inorganic nitrogen forms into organic compounds that serve as building blocks for cells and tissues. Two forms of nitrogen are predominately used for assimilation, ammoniacal and nitrate nitrogen. Because ammoniacal nitrogen is more reduced energetically than nitrate, it is often preferred over the latter by plant species for assimilation, more so in habitats with restricted nitrification (Garnett *et al.* 2001). The nutrient uptake by macrophytes is limited by its growth rate and the saturation concentrations of nutrients in the plant tissue (Vymazal 2007). Plant tissue analysis and quantification of the harvested biomass together thus represents the nutrient uptake capacity of a specific plant species. Both *Typha latifolia* and *Canna indica* showed similar total nitrogen and phosphorous concentrations (Table 3 and Supplementary Table S2). However, the sulfur concentration in the *Typha latifolia* tissue was significantly higher (7,158 mg/kg) than that of *Canna indica*. However, harvesting of biomass or different growth stage of the macrophytes has little impact on the overall sulfate removal observed in the constructed wetland. Chen *et al.* (2016), in their lab-scale studies with constructed wetlands operated in batch mode with secondary effluent, reported that while *Typha latifolia* had little effect on sulfate removal, unless organic carbon is available in its root zone. Thus, root-zone microbial biodegradation seems to be the dominant factor influencing sulfate removal in the CW. The potassium concentration in *Canna indica* tissue was consistently very high (greater than 40,000 mg/kg) over the entire study period Table 4. The area (10 m × 4 m) vegetated with *Typha latifolia* and *Canna indica* in the CW being identical, the harvested biomass and plant tissue concentrations, give a fair estimation of the biomass yield potentials. An automatic weather station located in the Zilla Parishad High School (ZPHS) premises (latitude: 18.25696°; longitude: 78.58109°) of the village ensured availability of accurate weather data throughout the study period. Being semi-arid village the rainfall is low and sparse. Distinct seasonal variation was not observed in the plant growth rate measured from weight of the biomass harvested (Table 4). Growth rate for *Typha latifolia* and *Canna indica* were 0.196 kg/m^2/day and 0.204 kg/m^2/day, respectively. Detailed morphological study of the macrophytes although was beyond the scope of this field-scale study conducted in a

Table 4. Fresh weight of the plant biomass harvested from the constructed wetland during the study period (from 30 m^2 area for each of the two plant species).

	Plant biomass (kg)	
Month of harvesting	*Typha latifolia*	*Canna indica*
Aug-15	207	212
Oct-15	302	321
Nov-15	381	388
Jan-16	346	353
Feb-16	316	337
Apr-16	415	427
May-16	430	442
Jul-16	426	458
Total	2,823	2,938

Table 5. The nutrient concentrations observed in the top layer sand in the constructed wetland.

Parameters	At start (mg/kg)	*Typha latifolia* cell (mg/kg)	*Canna indica* cell (mg/kg)
Total-Nitrogen	15	439	467
Total-Phosphorous	66	188	188
Exchangeable-K	0.05	29.57	31.35
Exchangeable-Ca	1.1	970.72	966.5
Exchangeable-Mg	0.2	109.39	104.5
Available-Fe	1.79	17.91	11.44
Available-Zn	0.6	1.36	2.56
Available-B	0.13	0.13	0.235
Available-S	4.15	12.29	9.245

village. The study found the nitrogen and phosphorous uptake potential of both *Typha latifolia* and *Canna indica* were similar. The results also demonstrated the higher sulfur and potassium uptake potential of *Typha latifolia* and *Canna indica*, respectively. The biomass yield obtained from the constructed wetland highlighted the revenue generation potential through the utilization of the harvested biomass for composting or biogas production.

Nutrient accumulation in the CW media

The concentration of nutrients in the sand sampled from the top layer of the CW at the start and end of this study is presented in Table 5 to give an idea of the nutrient accumulation (Supplementary Table S3). The high growth rate and dense foliage of both the *Typha latifolia* and *Canna indica* ensured minimal weed invasion. The nitrogen, phosphorous and potassium accumulations in both the sand layers of both the *Typha latifolia* and *Canna indica* vegetated surfaces were identical.

Reuse of the treated water

The average ammoniacal nitrogen concentration being 34.6 mg/L of wastewater exhibited significant eutrophication potential if is released in the water bodies untreated. Moreover, usage of nutrient reach untreated wastewater leads to weed formation, particularly during the post-germination and early stages of the crop. The average inorganic nitrogen removal efficiency observed in the CW was 61%. Thus, CWs entrap excessive inorganic nitrogen as plant biomass and makes the treated wastewater better suited for fertigation irrespective of crop growth cycle. The inorganic nitrogen thus entrapped in the plant biomass can be brought back to soil through composting process improving the nutrient use efficiency of these resource poor rural communities. Common flood irrigation method requires about 500 m^3/ha water per irrigation event. Thus, the use of the treated wastewater for fertigation (Licata *et al.* 2019) led to the addition of 7.5 kg/ha of nitrogen in the fields per irrigation. The treated wastewater was utilized by a local farmer to cultivate the 0.6 ha agricultural land adjacent to the treated wastewater storage tank. The farmer had no access to any other source of irrigation for cultivation in this plot. The *kharif* 2015 being a drought year in the region, the farmer was keen for additional income using the treated wastewater during the *rabi* season. The farmer cultivated chickpea (variety: JAKI 9218) during December 2015 to February 2016. The germination efficiency observed was 93% and a net cost of cultivation was about Rs. 6,000, mainly toward labor cost during field preparation. During this period, the farmer used the treated wastewater for two irrigation events. As is the local practice, the whole harvest (entire plants) was sold for Rs.50,000 as Haribot or green chickpea. Subsequently, the farmer also cultivated sweet corn during March to May 2016 (dry-summer months) period using the treated wastewater. The farmer could give only 5 irrigations, *i.e.*, one short of the required number of irrigation, as the peak summer season saw a reduction in wastewater flow. This might be the reason for the slightly lesser yield (10 t/ha) which was slightly lesser than the 11.25 t/ha yield obtained by the local farmers using bore water for irrigation with identical agricultural practice. The grains from bore water as well as treated wastewater irrigated fields were compared through elemental analysis and were physically and chemically indistinguishable. Soil samples were collected (Sahrawat *et al.* 2008) from the bore-water as well as the treated wastewater irrigated plots and no significant detrimental effect of the treated wastewater irrigation was observed on soil health (Table 6). The total harvest of 6 tons of this sweet corn was sold at variable (Rs. 6,000 to Rs.15,000 per ton) rates and the total sell value obtained was Rs.60,000. The cost of cultivation constituted of labor cost (Rs. 9,500); seed (variety: SUGAR 75, Syngenta) cost (Rs. 10,000) and fertilizer cost (Rs. 11,500). The fertilizer used was NPK (14-35-14) and urea each of 50 kg/acre. The progressive farmer could give a breakup of the labor cost, which was comprised of the following activities: cultivation and field preparation (Rs.3,600); sowing (Rs. 1,000); fertilizer application (Rs. 400) and inter-cultivation (Rs. 4,500). The seed price and water availability were the main limiting factors that restricted the size of the cultivated area. During the rainfed *kharif* season of 2016, the farmer cultivated maize without any use of the treated wastewater. However, the assurance of treated water availability although gave the farmer confidence to go for rainfed cultivation, after suffering crop loss due to poor rainfall during the previous *kharif*.

Reuse of the biomass harvested from the constructed wetland

As mentioned plant biomass was harvested from the constructed wetland at a frequency of 45 days. The harvesting activity (including the fresh weight estimation) required two labor for a single day. This was the only operating cost incurred for the overall wastewater treatment scheme. The

Table 6. Soil analysis data before and after the sweet corn cultivation in treated as well as bore-well irrigated plots.

Sl.No	Parameters	Unit	Bore-water irrigated	Treated wastewater irrigated
1	Total-K	mg/kg	3,678.80	4,243.00
2	Total-Ca	mg/kg	25,449.99	25,565.52
3	Total-Mg	mg/kg	13,313.50	13,150.22
4	Total-Na	mg/kg	938.61	980.14
5	Total-Fe	mg/kg	54,341.19	56,469.19
6	Total-Cu	mg/kg	104.68	108.63
7	Total-Mn	mg/kg	727.86	769.91
8	Total-Zn	mg/kg	75.52	76.86
9	Total-S	mg/kg	181.87	191.61
10	Total-B	mg/kg	190.13	197.80
11	Total-As	mg/kg	BDL	BDL
12	Total-Cd	mg/kg	4.98	5.11
13	Total-Co	mg/kg	28.60	29.03
14	Total-Cr	mg/kg	59.10	63.98
15	Total-Pb	mg/kg	BDL	BDL
16	Total-Ni	mg/kg	51.90	53.62

BDL: Below detectable limit of ICP-Mass spectra.

help of local farmers who were the prime beneficiaries of the treated wastewater and biomass was utilized to carry-out this maintenance operation who did carry out the harvesting in exchange of the free harvested biomass. The average fresh weight of the biomass harvested each time was about 500 kg (Table 4). The biomass helped to supply fodder for the two bulls (a critical livestock asset) of the adjacent farmer using the treated wastewater throughout the year. It is worth mentioning these were the only two bulls in the entire village and fodder shortage is a serious issue that makes keeping bulls uneconomical for these farming families. The ability to keep the bulls helped the farmer to prepare and maintain energy requirements of crop cultivation.

Sustainability of the CW

Compared to conventional wastewater treatment technologies, operation of CWs does not require electricity, chemicals or skilled supervision. However, the technology cannot be popularized as a 'maintenance free' technology. Often in the eagerness to get villagers' approval this part remains unclear to the villagers which in the long-run may jeopardize the implementation scheme. Routine harvesting of the plant biomass and cleaning of debris in the drains upstream to the CW, particularly near the bar-screens ensure smooth functioning of the decentralized wastewater treatment (DWAT) unit. Awareness campaign helped to garner support for cleaning of drains frequently by the Gram Panchayat. Nevertheless, maintenance of the DWAT unit required 3 human-days labor every 45 days which approximately costs Rs. 900 (US$14). A user group was created involving beneficiaries of the harvested biomass and treated wastewater. Members of the gram panchayat were also made part of the user group. User groups help to delineate roles and responsibility toward maintenance of the DWAT, moreover members ensured long-term sustainability of the DWAT unit through synergy with other on-going government schemes such as Swachh Bharat Mission (SBM) and Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA). Technical handholding and capacity building of the user group throughout the length of study period helped the local community to become self-sufficient toward the operation and maintenance of the DWAT unit in Kothapally. Beyond the tangible benefits such as improved wastewater management, increase water use efficiency and increase availability of fodder the intangible benefits of these DWAT units would be reduced occurrence of pest and vector borne diseases and environmental pollution. It is difficult to quantify although as in these resource poor villages, frequency of disease occurrence and wellbeing gets affected by diverse factors such as access to safe drinking water, nutritious food and vaccination. The activity serves as a win-win-win proposition by addressing issues of health and hygiene, raw wastewater irrigation, water scarcity, reducing agricultural water demand and recycling of nutrients to soil.

Conclusion

The study demonstrated how a constructed wetland can be operated by villagers themselves to treat the wastewater generated from their households. The high removal efficiency observed for coliform and total suspended solids consistently highlights the reliability of the technology and its potential to abate raw wastewater irrigation. This approximately $10,000 technology with negligible operation and maintenance cost facilitated revenue generation of $1,000 in the first year itself while the intangible impact observed was improved raw wastewater management.

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