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Constructed wetlands and solar-driven disinfection technologies for sustainable wastewater treatment and reclamation in rural India: SWINGS project

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ABSTRACT

SWINGS was a cooperation project between the European Union and India, aiming at implementing state of the art low-cost technologies for the treatment and reuse of domestic wastewater in rural areas of India. The largest wastewater treatment plant consists of a high-rate anaerobic system, followed by vertical and horizontal subsurface flow constructed wetlands with a treatment area of around 1,900 m^2 and a final step consisting of solar-driven anodic oxidation (AO) and ultraviolet (UV) disinfection units allowing direct reuse of the treated water. The implementation and operation of two pilot plants in north (Aligarh Muslim University, AMU) and central India (Indira Gandhi National Tribal University, IGNTU) are shown in this study. The overall performance of AMU pilot plant during the first 7 months of operation showed organic matter removal efficiencies of 87% total suspended solids, 95% 5-day biological oxygen demand (BOD_5) and 90% chemical oxygen demand, while Kjeldahl nitrogen removal reached 89%. The UV disinfection unit produces water for irrigation and toilet flushing with pathogenic indicator bacteria well below WHO guidelines. On the other hand, the AO disinfection unit implemented at IGNTU and operated for almost a year has been shown to produce an effluent of sufficient quality to be reused by the local population for agriculture and irrigation.

Key words | anodic oxidation, developing countries, hybrid treatment wetland, UV disinfection, water reuse

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INTRODUCTION

Cooperation, knowledge and technology transfer from the European Union (EU) to low-income countries have increased in the last decades as a result of the improved welfare of the European region, the interest of the EU in sharing technical and scientific innovation developments, and the commitment to benefit and improve life standards of the population in developing regions. Additionally, in most low-income countries, where economic conditions and life quality are improving, the population growth is constant. As a result, more industrialization, an increase of wastewater discharges and greater demand for agricultural production imply a larger demand for suitable water.

India is the second most populous country in the world with ca 1.2 billion inhabitants, and ranked as the seventh largest country in regard to surface (CIA 2015). In the past 25 years water supply and sanitation in the subcontinent have been developing steadily and the Indian Government has striven to meet the UN Millennium Development Goal (MDG) which calls for reducing the unserved population by 50% by 2015. According to WHO/UNICEF (2015), in the period between 1990 and 2011, while India's population increased by around 30%, management of water in urban areas has been boosted, and currently 60% of the urban population is covered by sewers and treatment systems. Open defecation in urban areas has also decreased by 50% in this period. Within the same time span, technical wastewater management in rural areas – where nearly 70% of the population lives – has also been improved, and national coverage has increased from 7% to 24%, while open defecation has gone down from 90% to 60%. Even though India has invested resources and gone a long way in the last years in improving the sanitation situation, there is room for improvement, as well as for the implementation of technology that can provide adequate treatment, under beneficial economic conditions, thereby generating positive environmental, health and social effects (DST 2011).

Understanding the importance and need for cooperation, both India and EU member states have set the stage for jointly working to address these challenges. The main objective of 'Safeguarding water resources in India with green and sustainable technologies' (SWINGS) is to develop low-cost optimized treatment schemes employing state of the art wastewater management and treatment systems to make full use of water resources at community level, with the final purpose of tackling water scarcity in India. Sustainable solutions in rural India will require point-of-use or community-scale water treatment systems that reckon on locally available resources and expertise.

Constructed wetlands (CWs) constitute a nature-based technology resembling the decontamination processes occurring in natural wetlands, which has proven to be very efficient and convenient for decentralized treatment of wastewater. Compared with conventional wastewater treatment systems, usually based on activated sludge, CWs are low cost and easy to operate and maintain. Moreover, they present good integration into the natural environment, promoting wildlife, and acting as recreational areas. This makes the technology an attractive alternative which has a potential for application in low-income countries (Zhang *et al.* 2014), especially in rural settings where land limitation is less of an issue. Despite the technology having mainly been implemented and developed in Europe and the USA, in the last decades CW systems have found wide implementation in subtropical and tropical regions in countries like Brazil (Machado *et al.* 2017) or China, where about 500 systems were constructed between 1990 and 2010 (Zhang *et al.* 2012). The technology has also been widely implemented in central and Eastern Europe, where there is a relatively higher proportion of inhabitants living in small rural settlements than in Western Europe (Istenič *et al.* 2015). These are implemented either alone or in combination with other technologies and have been used to treat a wide range of pollutants, including urban wastewater, runoff, landfill leachate, hospital effluent, agricultural waste and many industrial effluents.

Although waste stabilization ponds have been historically used in India either as polishing treatment step or for wastewater-fed aquaculture (Jana 1998; Patra *et al.* 2012), subsurface flow CW technology has not yet found widespread use in the country, where sewage management in rural settings has been vastly neglected. Just a few examples exist, being mostly of horizontal flow (Juwarkar *et al.* 1995; Billore *et al.* 1999, 2008; Rai *et al.* 2015). One of the main constraints for their implementation at a local scale is the lack of local expertise and the adaptation of the technology to the local conditions (e.g. vegetation, locally available materials, climate, water quality, etc.). CWs constitute a promising alternative for decentralized wastewater treatment in rural India, where the great majority of towns lack sewerage network using lined drains, and oftentimes unreliable electrical power supply, thus demanding sustainable solutions requiring minimal investment and unsophisticated operation. CWs are particularly well suited to this need, given their flexibility, operational simplicity and effectiveness.

The SWINGS project has succeeded in closing the water loop by achieving integral wastewater treatment and reclamation at the campus of Aligarh Muslim University (AMU) (Aligarh, Uttar Pradesh, Northern India), and has also implemented tertiary treatment and effective disinfection units testing different technologies at Indira Gandhi National Tribal University (IGNTU) (Lalpur and Amarkantak, Madhya Pradesh, Central India), and at the International Center for Ecological Engineering of the University of Kalyani (Kalyani, West Bengal, Eastern India). The integral treatment system designed and built at AMU aims to provide full wastewater treatment through the use of various technologies (i.e. horizontal and vertical flow CWs, two solar-driven disinfection units). The system in IGNTU receives insufficiently treated wastewater, which is filtered through a CW to reach the needed quality for further disinfection in a solar-driven anodic oxidation (AO) unit. The current manuscript presents the design, implementation, start-up and performance of these two systems. Further information is given in the Supplementary Material, available with the online version of this paper.

MATERIAL AND METHODS

Design and implementation of AMU pilot plant (Aligarh, Uttar Pradesh, India)

The pilot plant at AMU treats municipal wastewater generated at the campus for ca. 1,000 population equivalent. The plant was designed and constructed during the project implementation (2012–2016), and fully commissioned in January 2016. Wastewater is briefly stored in a homogenization tank before it flows into a primary treatment and a combination of CW systems followed by two solar-driven disinfection units. The primary treatment is achieved by means of an up-flow anaerobic sludge blanket (UASB) methanogenic reactor of 50 m^3. The secondary treatment consists of two parallel treatment trains of CW units. Each treatment train is fitted with a combination of an unsaturated vertical subsurface flow constructed wetland (VFCW) (480 m^2), followed by a horizontal subsurface flow constructed wetland (HFCW) (460 m^2). The design also includes flexibility in the operation, and is fitted with alternatives, allowing the recirculation of treated effluents to the different treatment structures to enable different operational options and exploitation strategies. Following the CWs, the plant is fitted with two solar-driven disinfection units: an ultraviolet (UV) and an AO system, each one designed to disinfect up to 10 m^3/d to be reused for toilet flushing, irrigation and aquaculture.

The parameters used for the plant design were obtained by characterization campaigns run by AMU along with historical water quality data (Table 1). The system treats ca. 200 m^3/d in an area of around 1,900 m^2. Additional areas are needed for the establishment of the primary treatment, pumping units, recirculation and sampling wells, and the water disinfection units.

Primary treatment: UASB reactor

Raw wastewater enters the plant through a bar screen and flows to a grit channel and a homogenization tank.

Table 1 | Wastewater characteristics from analytical work at AMU and national discharge standards (modified from Khalil *et al.* 2006; Khalil 2009; Ministry of Environment & Forest 2010)

Parameter	Raw sewage	Target
BOD_5 (mg/L)	210	<30
COD (mg/L)	450	NR
TSS (mg/L)	400	<50
VSS (mg/L)	250	NR
NH_4-N (mg/L)	32	NR
TKN (mg/L)	49	NR
FC (CFU/100 mL)	10^6–10^7	$<10^4$

NR: Discharge concentration not mentioned in the national discharge limits.

Subsequently, water is pumped to the UASB reactor (volume = 50 m^3), with a nominal hydraulic residence time of 6 h. Once the water is treated, the effluent is collected on the top part of the reactor by two gutters and conducted to a common effluent below the water level in the reactor. At the top, the reactor is fitted with a gas collection system. The gas-liquid-solid separator is built in reinforced plastic fibre and is connected with a flaring system to burn the excess methane produced by the anaerobic digestion. Table 2 indicates the design parameters of the UASB, while Figure 1 shows the blueprints of the same.

Secondary treatment: VFCW and HFCW

After the primary treatment, the system has two parallel treatment trains (west and east) both comprising vertical subsurface flow (VF) followed by horizontal subsurface flow (HF) CWs, with wells and structures to allow sampling, recycling and hydraulic control (Figure 2). Initially, both trains treat equal water volumes, but the flow can be regulated at will and different loadings can be treated, thus increasing the flexibility for research and treatment capacity. The treatment trains are loaded using two different methods; the western train is fed using a siphon that works without the use of electricity, while the eastern train is loaded using an electric pump.

Table 2 | Design parameters for the UASB reactor of AMU plant

Parameter	Values	Unit
Dimensions (length/width/depth)	3.54/3.04/4.87	m
Volume	51.13	m^3
Sludge bed concentration	65–75	kg TSS/m^3
Upflow velocity	0.52–0.54	m/h
Minimum hydraulic retention time (HRT)	7.0	h
Sludge residence time (SRT)	35–40	Days
VSS destruction in reactor	50	%

Two plant species were selected for the VFCW, namely *Phragmites australis* and *P. karka*, planted at a density of 4 plants/m^2. Additional materials were used for the construction, including liners to avoid the infiltration or gain to or from groundwater (Figure 3); membranes and geotextiles were used to separate the layers in the beds.

Each VFCW is fitted with recirculation wells. Effluent recycling has proven to be a good strategy to enhance the performance of CW systems (Arias *et al.* 2005; Torrijos *et al.* 2016; Ávila *et al.* 2017; Bohórquez *et al.* 2017), and as such the system can regulate the recirculation rates for research purposes and to improve the quality of the treated water. The recirculation unit has different functions: diluting the new wastewater, therefore reducing the risk of clogging in the CW and maintaining homogeneous influent water characteristics; enhancing total nitrogen removal by allowing further denitrification of the nitrified effluent; removing H_2S, reducing the potential fouling smell, preventing the erosion of concrete structures and prolonging the lifetime of the pump; and helping to determine design parameters to optimize the CW technology in India.

The HF beds provide a final water polishing step, enhancing nitrogen elimination as well as the removal of pathogens (Molle *et al.* 2008; Ávila *et al.* 2013b). Since HFCWs are water saturated, dissolved oxygen (DO) availability is limited in the bed and organic carbon is available from root exudates, denitrification of the nitrate nitrogen up to nitrogen gas being the major nitrogen transforming process (Zhai *et al.* 2013; Adrados *et al.* 2014). HF beds were planted with equal surfaces of arrow head (*Sagittaria sagittifolia*), iris (*Iris spp.*), and canna (*Canna indica*), tropical species with flowers with nutrient removal potential, to beautify the site, increase the acceptance by the local population, and even act as a revenue generator.

The effluent of the HFCWs is collected in a 1.8 m deep well, from where about 10% of the final effluent is pumped and disinfected using the two solar-powered units. The remaining 90% of treated water flows by gravity to a channel to be reused for irrigation in the surrounding agricultural plots.

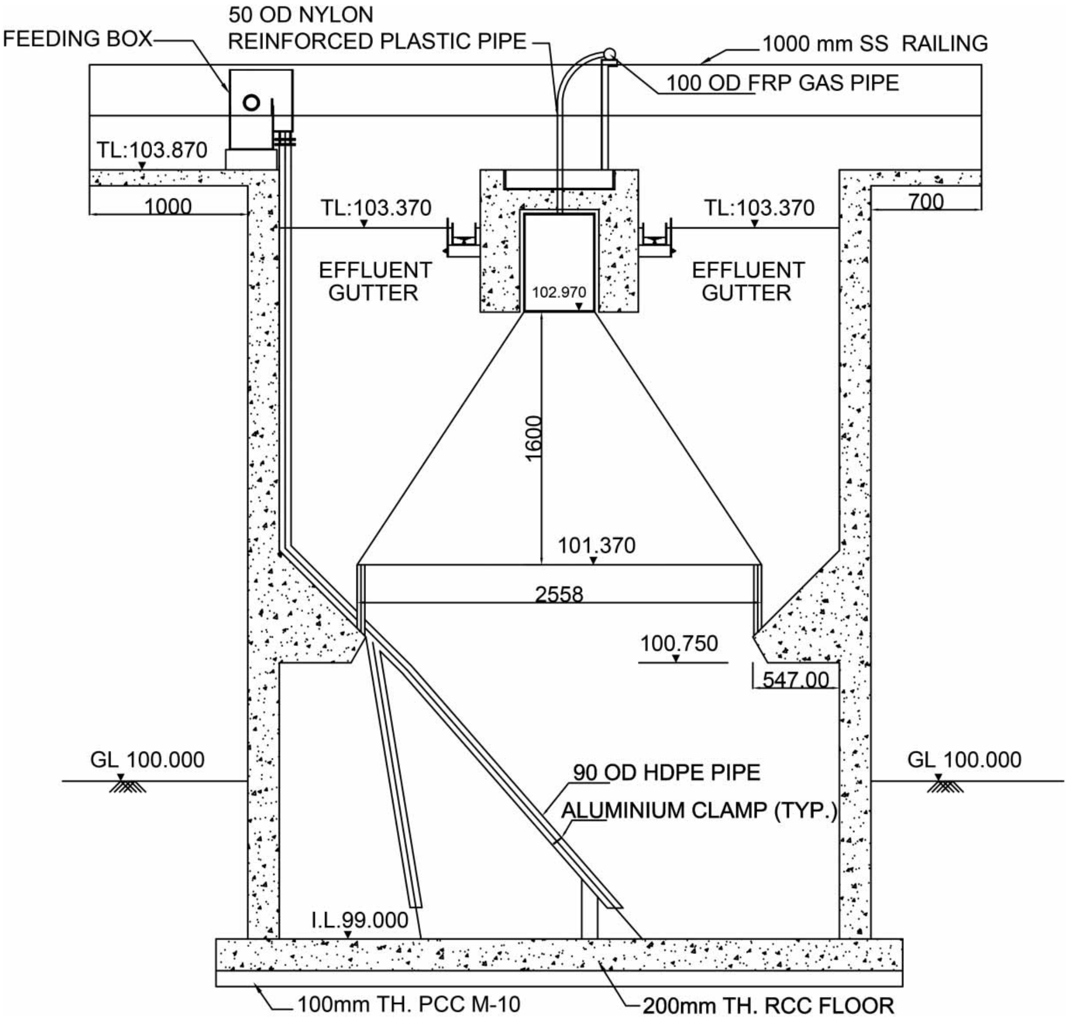

Figure 1 | Engineering drawings of UASB reactor at AMU pilot plant.

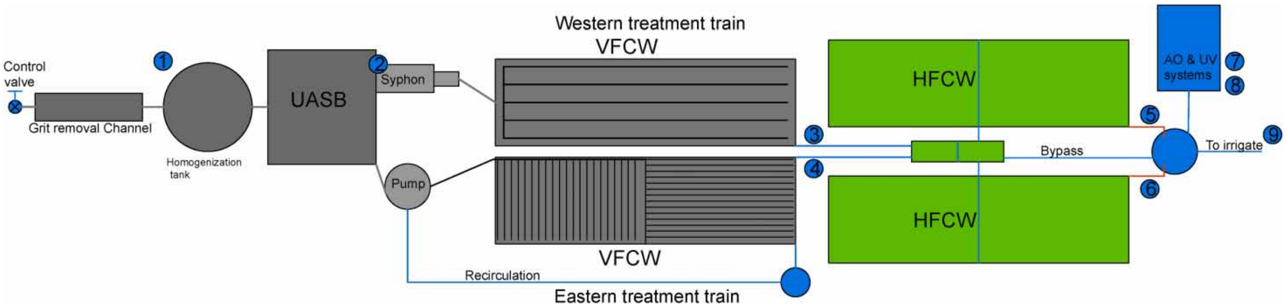

Figure 2 | Flow chart of AMU pilot plant with both treatment trains (west and east). Sampling points along the water treatment line of AMU pilot plant are also indicated.

Disinfection treatment: solar-driven UV and AO units

The criteria for selecting the disinfection systems included the use of effective field proven technologies with low establishment and maintenance investment, low or no energy demand and minimum potential to form harmful by-products. Those selected were solar-driven technologies based on AO and UV disinfection, which receive the CW system effluent by means of two electrical pumps installed in the final well.

Figure 3 | Implementation phases of vertical subsurface flow constructed wetlands.

The AO unit is an autonomous system developed by Autarcon™ that disinfects water by a combination of processes that include a filtration step followed by the electrolysis of salts already present in the water to produce free chlorine. On the other hand, the solar UV system is an autonomous system developed by Solarspring™ that uses a UV lamp emitting light at wavelengths between 240 and 280 nm to inactivate pathogens. Figure 4 shows the flow chart of the solar-driven UV system implementation.

Design and implementation of IGNTU pilot plant (Amarkantak, Madhya Pradesh, India)

At IGNTU, a tertiary treatment system was designed and implemented at the campus premises. As the minimum

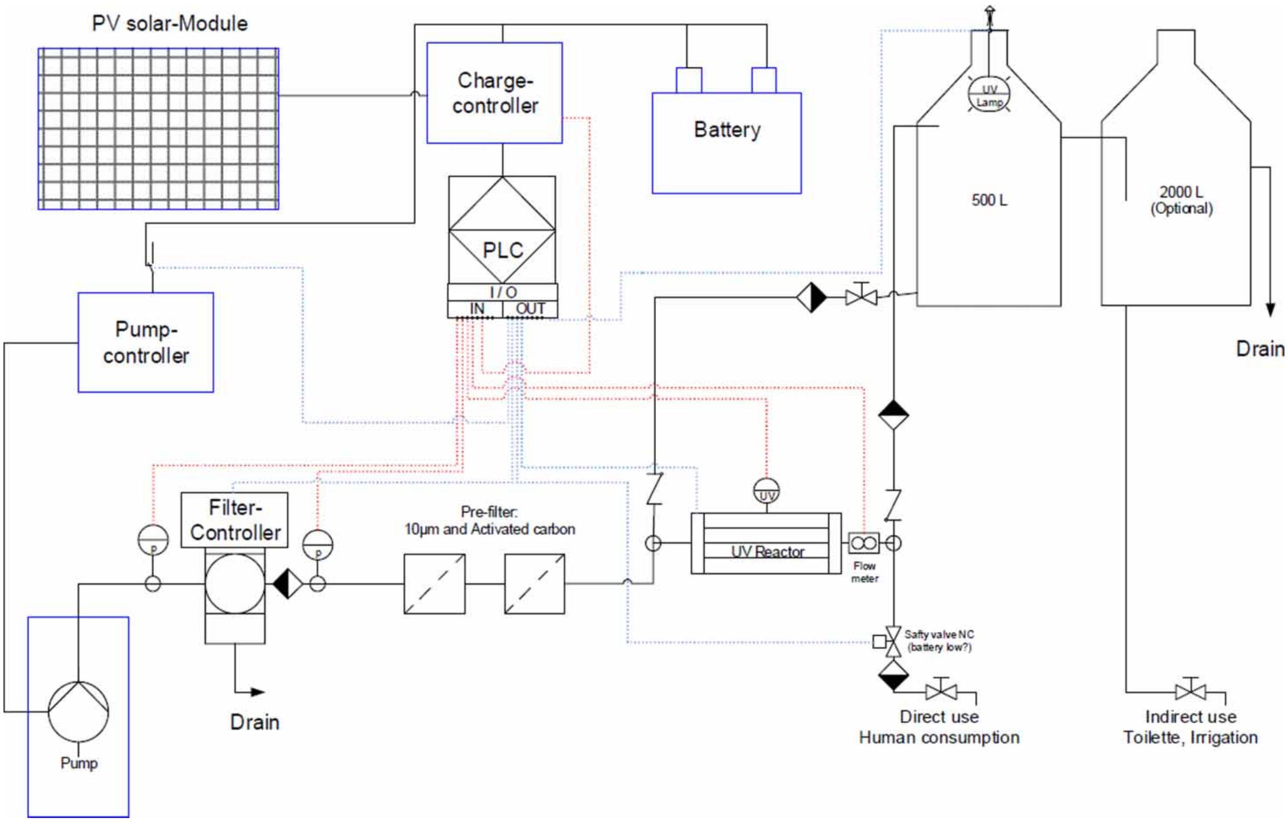

Figure 4 | Flow chart of solar-driven UV disinfection implemented at AMU pilot plant.

required effluent water quality is not achieved by the existing sewage treatment plant (STP), a direct application of solar-driven AO disinfection was not possible, since all the produced chlorine would become consumed by the organics before having effect on the pathogens. Therefore, a 35 m^2 (3.5 m × 10 m) horizontal subsurface flow (HF) CW was installed to pre-treat the effluent of the STP of the IGNTU campus, so as to remove organic matter and turbidity (Table 3). Figure 5 presents the technical drawings and design parameters of the HFCW at IGNTU, while Figure 6 shows its construction and implementation.

Even though the HFCW reduces the turbidity, this can be still higher than desired, and therefore a solar-driven and automated back washable turbidity filter was developed and installed filled with Ag Plus zeolite media (Figure 7).

Table 3 | Influent and effluent physico-chemical characterisation of IGNTU campus STP. All data were collected from plant managers.

Parameter	Raw wastewater	IGNTU STP effluent
pH	7.86	8.3
Temperature (°C)	29	29.8
Conductivity (µS/cm)	1405–2250	700–1420
Total dissolved solids (mg/L)	702–1124	330–709
Chloride (mg/L)	56–115	40–71
BOD_5 (mg/L)	150–349	30–80
COD (mg/L)	209–450	70–190

Water quality sampling and analysis

The AMU pilot plant has been in continuous operation for about 7 months since its commissioning and regularly monitored at various sampling campaigns, while treating about 200 m^3/d of municipal wastewater. During this period, recirculation was still not applied. Sampling took place weekly by taking grab samples at the effluent of each treatment unit, which are indicated in Figure 2. The *in-situ* parameters were measured directly in the sampling wells, while grab samples were taken, refrigerated and transported to the laboratory to be analyzed immediately upon arrival.

The IGNTU pilot plant was also commissioned at the end of 2015. Since its establishment, the system has been treating partially treated wastewater and several sampling

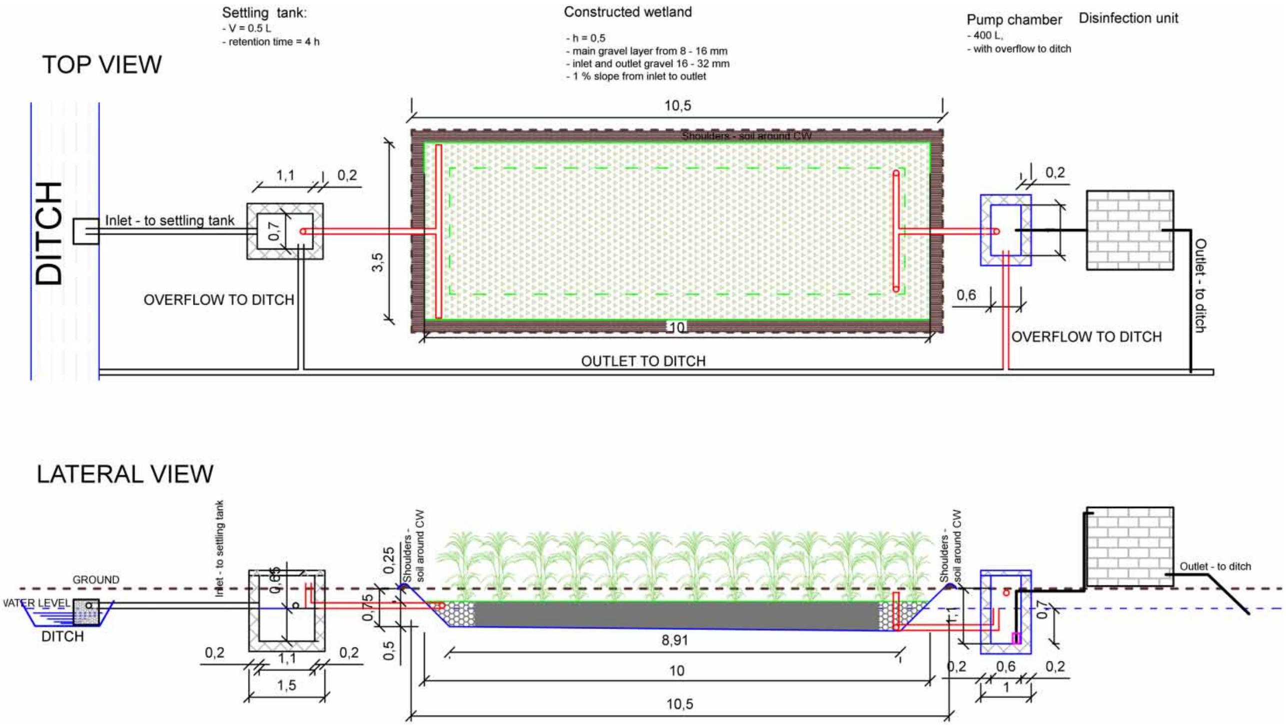

Figure 5 | Drawings and design parameters of the horizontal subsurface flow CW implemented at IGNTU site.

Figure 6 | Horizontal subsurface flow bed construction and implementation at IGNTU pilot plant.

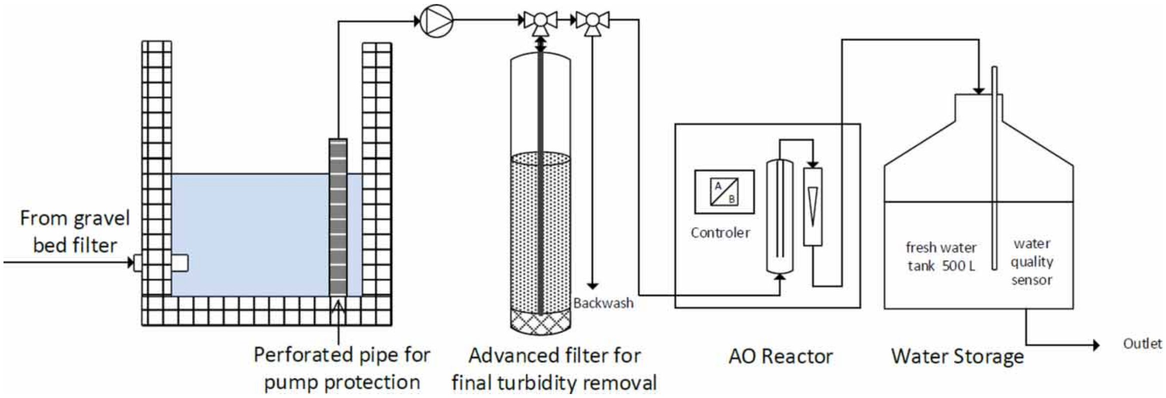

Figure 7 | Setting of the solar-driven AO disinfection unit implemented at IGNTU campus.

campaigns have been conducted for about 8 months. Grab samples were taken monthly at the influent and effluent of the HFCW and at the effluent of the AO system and transported immediately to the laboratory for analysis.

The *in-situ* water quality parameters including water temperature, DO, pH, turbidity, redox potential (ORP) and electric conductivity were determined using commercial calibrated electrodes. Laboratory water quality analysis of total suspended solids (TSS), volatile suspended solids (VSS), chemical oxygen demand (COD), 5-day biological oxygen demand (BOD_5) and ammonium nitrogen (NH_4-N) followed *Standard Methods* (APHA 2012). TSS and VSS were determined following APHA 2540 D, ammonia nitrogen following spectrophotometric method APHA 4500 NH_3-D and nitrate spectrophotometric method APHA $4500-NO_3^-$F. Phosphate was analyzed following spectrophotometric method APHA 4500-P F, and COD samples were analyzed following APHA 5210 C. Total Kjeldahl nitrogen (TKN) was determined using a Foss™ Tecator™ Kjeltec™ 8200 Auto Distillation Unit. Finally, BOD_5 samples were analyzed by APHA 5210 Biochemical Oxygen Demand.

Pathogenic indicator bacteria were examined using the multiple tube fermentation technique from *Standard Methods* (APHA 2012), namely 9221 B for total coliforms (TC), 9221 E for fecal coliforms (FC), 9221 F for *Escherichia coli*, 9230 B for enterococci. *Salmonella* and *Clostridium* were evaluated using filtering technique. For *Salmonella*, the APHA method followed was 9260 B, while *Clostridium* was evaluated following the UK environmental protection office, Part 6 – Methods for the isolation and enumeration of sulphite-reducing clostridia and *Clostridium perfringens* by membrane filtration.

The flow entering the CW treatment lines was measured indirectly by using a pulse counter installed in each of the feeding wells, which tallies the number of times the siphon and pump empty the well during a day. Since the capacity of the siphon (west treatment line) and the pump (east treatment line), the dimensions of the feeding chambers and the water level at each pulse are known, the flow loading into the west and east vertical beds could be accurately calculated.

Statistical analysis was performed using repeated one-way analysis of variance (ANOVA), and post hoc Tukey's HSD tests were conducted to compare all water quality parameters and pollutant concentrations from different treatment units with the significance level of $p \leq 0.05$. All data were tested for homogeneity of variance by Levene's test before the statistical analysis. The statistical analysis was carried out with XLStat Pro® statistical software (XLStat, Paris, France).

RESULTS AND DISCUSSION

Treatment performance of AMU pilot plant

Figure 2 shows the sampling points where the first sample corresponds to the influent of the two VF beds. Since the UASB had not yet reached a steady state operation at the time of this study, showing an irregular performance, it was by-passed while reaching optimal operation conditions. Sampling points 2 and 3 correspond to the effluent of the two VFCW (east –VE- and west –VW-); 5 and 6 correspond to the effluent of the HF beds (east –HE- and west –HW-), and 6 and 7 correspond to the effluent of the AO and UV systems.

If the mass loading is considered, the loads applied into the VF beds were relatively low, of approx. 30 g COD/m^2d, 13 g BOD_5/m^2d, 7 g NH_4-N/m^2d and 8 g TSS/m^2d. These are around half of the reported organic loading rates recommended for warm climates (60–70 g COD/m^2d)

(Hoffmann et al. 2011) and slightly lower than those suggested for subtropical climates in Brazil (40 g COD/m^{2}d, 10 g NH$_4$-N/m^{2}d) (Sezerino et al. 2012). Therefore, it is expected that the system has even a larger capacity to treat higher loads and will be optimized through gradually submitting increasing hydraulic loads (Ávila et al. 2014, 2017). The load removal rates for the water quality parameters varied largely between the treatment units. The VF beds were responsible for almost the complete removal of the influent organic load (removal of 27 g COD/m^{2}d and 10–12 g BOD$_5$/m^{2}d), and the remaining final effluent was below 0.2 g COD/m^{2}d. Ammonia nitrogen removal was higher in the west vertical unit (VW) (6.8 g NH$_4$-N/m^{2}d) than in the east vertical unit (VE) (3.5 g NH$_4$-N/m^{2}d).

The average concentration of DO in the raw wastewater was approximately 0.6 ± 0.3 mg/L (Figure 8). DO values in the effluent from the two VFCWs were significantly higher than in the influent, observing average values of 4.0 ± 1.3 mg/L in the VW and of 2.3 ± 1.2 mg/L in the VE. Subsequently, DO values slightly decreased (although with no statistical significance) after passage through the HFCWs, which are permanently saturated with water. In the VFCWs, the water is fed in large batches and then the water percolates down through the sand medium. The new batch is fed only after all the water percolates and the bed is free of water. This enables diffusion of oxygen from the air into the bed. As a result, VFCWs are far more aerobic than HFCWs and provide suitable conditions for nitrification (Brix & Arias 2005; Molle et al. 2008; Bohórquez et al. 2017), which has recently been shown to be carried out by not only bacteria but also archaea (Pelissari et al. 2017). Additionally, the higher performance of the VFCWs in comparison with the HF beds can be attributed to the fact that they are the first treatment step, and that the system is at its current operational period 'oversized' and can receive higher loadings, which is in accordance with previous studies with similar influent load and the exact same configuration (Ávila et al. 2013a, 2013b). The higher performance of the VW in regard to NH$_4$-N removal seems to be related to the feeding system, which is shown to be better through the use of the siphon.

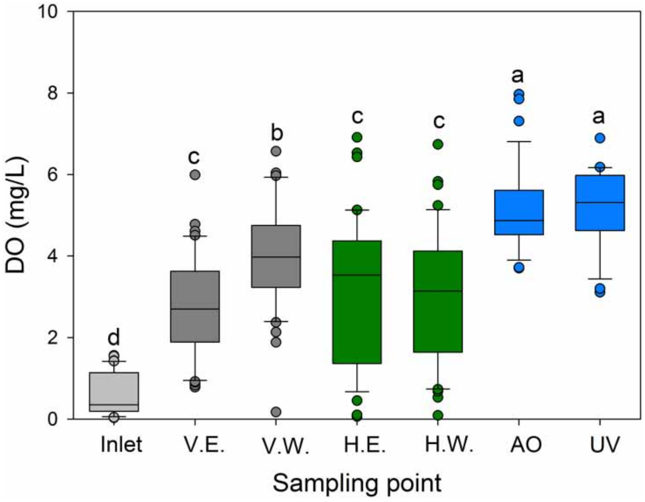

Figure 8 | Dissolved oxygen (DO) in influent and effluent of the two vertical (west -VW- and east -VE-), two horizontal (west -HW- and east -HE-) CWs and disinfection systems (AO and UV) of AMU pilot plant. Different letters above the bars in each plot represent statistically significant differences.

Table 4 shows the average concentration and standard deviation of different water quality parameters measured along the water treatment line, as well as the individual and overall removal efficiencies. TSS concentration at the inlet of the vertical beds was 41 mg/L and was effectively removed by the two VFCWs. The low concentrations were maintained along the rest of the system, producing a final effluent with an average TSS concentration of 5 mg/L, which is well below the discharge demanded by the national Environmental Protection Agency (Office of Water, EPA 821-F-16-002, June 2016).

The concentration of COD at the influent of the VFCWs was ca. 150 mg/L, and the beds produced effluent with average COD values of 20 and 28 mg/L COD for the west (VW) and east train (VE), respectively. Final effluent COD concentrations after the passage through the HFCWs were ca. 15 mg/L. With respect to BOD$_5$, average concentration before the VFCWs was 65 mg/L, and after the VF beds BOD$_5$ values decreased to 7 mg/L and 17 mg/L at the VW and VE effluents, respectively. As water flowed through the HFCWs the concentration of BOD$_5$ dropped to below 5 mg/L. After the disinfection systems the average concentration was below 3 mg/L.

Figure 9 illustrates the organic matter (COD (a) and BOD$_5$ (b)) and nitrogen (NH$_4^+$-N (c) and TKN (d)) concentrations of influent and effluent of all the treatment units at the pilot plant at AMU. Average influent COD, BOD$_5$, NH$_4$-N and TKN concentrations were 147 ± 42, 64 ± 19, 34 ± 2 and 39 ± 8 mg/L, respectively. All these pollutants were significantly removed in the system, and average concentrations at the effluent of CW systems were lower than 20 mg/L. The effluent concentrations of these pollutants were not significantly different between all the treatment units; besides, VE had significantly higher effluent pollutant concentrations than other treatment units. Solids retention and turbidity removal were efficient throughout the CW system, which is crucial for the correct functioning of the

Table 4 | Average and standard deviation of water quality parameters evaluated at the different sampling points of AMU pilot plant

	Inf.[a]	VE[b]	VW[c]	HE[d]	HW[e]	AO[f]	UV[g]	Overall removal efficiency (%)
TSS (mg/L)	41 ± 21	6.7 ± 4.4 (84)	5.1 ± 4.2 (87)	6.4 ± 5.7 (−11)	8.7 ± 10.3 (−50)	5.6 ± 2.7 (26)	5.4 ± 2.5 (29)	(87)
COD (mg/L)	147 ± 42	28 ± 18 (81)	20 ± 13 (87)	15 ± 9.6 (15)	17 ± 13 (2)	15 ± 11 (5)	14 ± 7.2 (7)	(90)
BOD_5 (mg/L)	64 ± 19	14 ± 6 (79)	7.1 ± 4.3 (89)	4.5 ± 2.5 (23)	4.4 ± 2.9 (24)	2.8 ± 1.9 (37)	2.9 ± 0.8 (34)	(95)
NH_4-N (mg/L)	34 ± 2.1	17 ± 10 (50)	0.8 ± 0.9 (98)	3.8 ± 3.1 (−64)	4.9 ± 4.8 (−109)	7.8 ± 4.2 (−81)	9.9 ± 3.7 (−128)	(74)
TKN (mg/L)	39 ± 8.1	12 ± 9.7 (70)	3.5 ± 4.1 (91)	4.5 ± 6.4 (−12)	5.5 ± 4.3 (−37)	5.3 ± 4.6 (−6)	3.1 ± 3.5 (38)	(89)
Turb[h] (NTU)	53 ± 23	7.1 ± 7.5 (86)	2.7 ± 5.9 (95)	1.5 ± 1.6 (31)	2.3 ± 4.4 (−9)	1.0 ± 0.5 (47)	0.9 ± 0.5 (54)	(98)

Individual and overall removal efficiencies (%) are indicated in brackets (*n* = between 12 and 54).

[a] Influent.

[b] East Vertical CW.

[c] West Vertical CW.

[d] East Horizontal CW.

[e] West Horizontal CW.

[f] AO disinfection system.

[g] UV disinfection system.

[h] Turbidity.

disinfection units. Average influent TSS concentration was 41 ± 21 (Figure 10), and final effluent values were below 10 mg/L. Likewise, the average turbidity at the influent of the VF beds was around 55 NTU. This was reduced to 3 NTU and 7 NTU in the VW and VE, respectively. By the passage through the HF beds, the average turbidity continued to decrease to ca. 1 NTU.

The elimination of Kjeldahl (TKN) and ammonia nitrogen (NH_4-N) showed a similar trend to the organic matter and solids removal. Influent concentration to the VFCWs was slightly below 40 mg/L for both forms of nitrogen. The VW bed nitrified almost all the influent NH_4-N, while the VF in the eastern train only nitrified about half of the NH_4-N reaching the bed. After the VF beds, water flowed through the HFCWs, and NH_4-N and TKN at the final effluent ranged between 3 and 9 mg/L. Since the environmental conditions in the saturated HF beds do not benefit the nitrification process, no nitrification is shown after the VF beds. The plant design, namely unsaturated beds (VF) followed by saturated beds, is aimed at removing nitrogen following the classic nitrification-denitrification pathway (Vymazal 2013). Although there are differences between the two beds at the present loading rates, the VF wetlands are performing as expected and are capable of nitrifying. The denitrification process is to occur in the saturated HF beds, where the previously nitrified ammonia nitrogen (NO_x) is to be converted into nitrogen gas by denitrifying bacteria under anoxic conditions and when sufficient carbon is present (Liu *et al.* 2016). Further experiments in the treatment system will include the determination of total nitrogen so as to evaluate the denitrification capacity. The overall percentage removal (previous Table 4) for all the examined water quality parameters ranged from around 74% for NH_4-N to 98% for turbidity. TSS, BOD_5 and COD average removal efficiencies were 87%, 95% and 90%, respectively. Most of the removal occurred while water trickled down in the VFCWs. The fact that the removal efficiency of NH_4-N and TKN was lower in the VE than in the VW (50% NH_4-N and 70% TKN at VE vs. 98% NH_4-N and 91% TKN at VW) can be explained by the loading scheme of the bed. While the VW is loaded by spaced pulses, the VE is loaded at shorter intervals, and therefore there is less time for the bed to be saturated with air before the next pulse is distributed on the surface of the bed (Molle *et al.* 2006). In addition, an increase of NH_4 in HFCW can be due to plant decomposition and self NH_4 production inside the wetland. The effect of the self-decomposition is more significant when a very low concentration (below 5 mg/L in case of NH_4 in HFCW – Table 4) is measured in the wetlands (Álvarez & Bécares 2008; Ávila *et al.* 2017).

The efficiency of the vertical and horizontal subsurface flow systems of AMU pilot plant was in line with the performance of similar treatment configurations at full-scale working at similar temperature and organic loads (Ávila

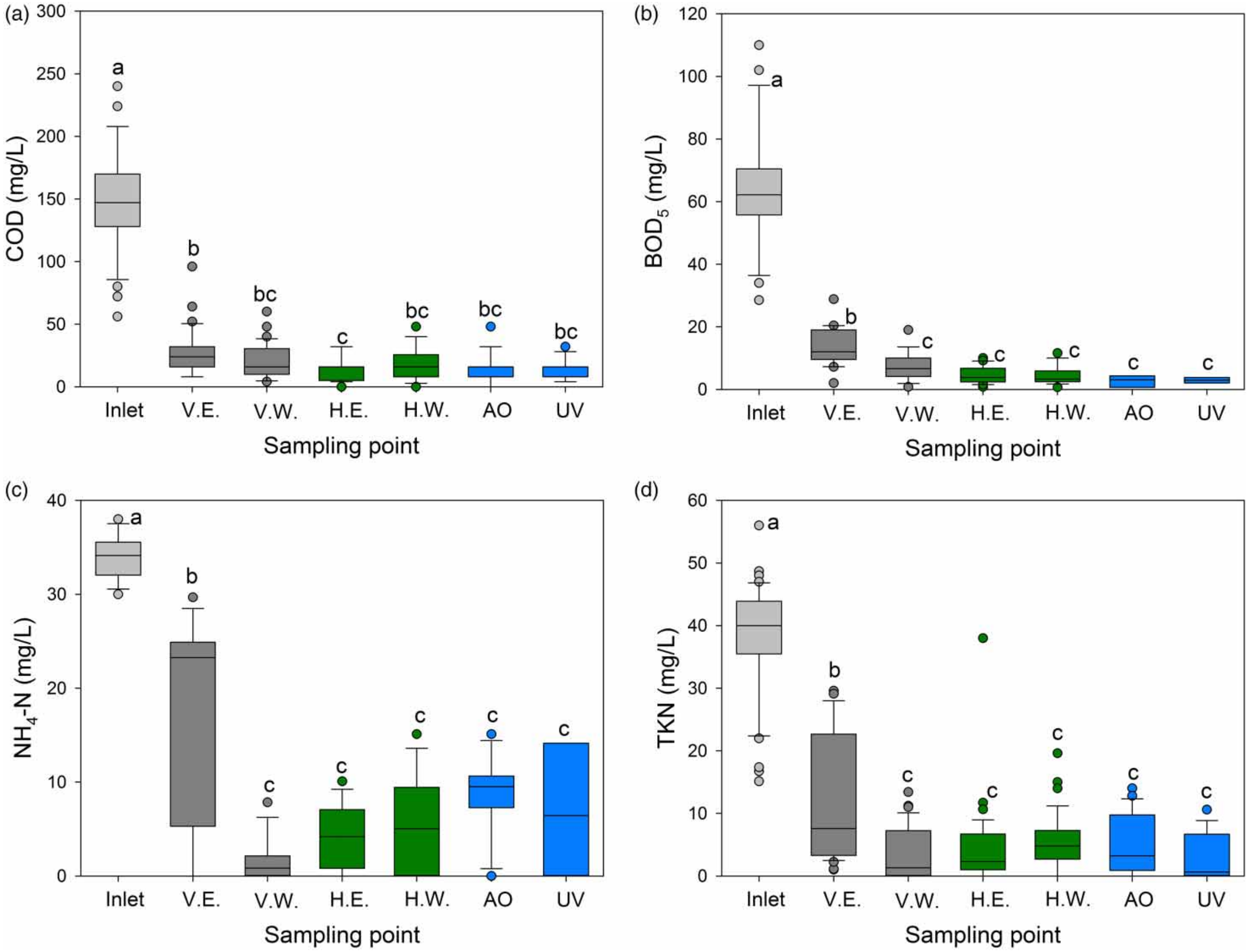

Figure 9 | COD (a), BOD$_5$ (b), NH$_4^+$-N (c) and TKN (d) concentrations in influent and effluent of the two vertical and two horizontal CWs and disinfection systems of AMU pilot plant. Different letters above the bars in each plot represent significant differences.

et al. 2013b; Vymazal 2013; Horn *et al.* 2014; Zhang *et al.* 2014). It is important to remark that the results of AMU pilot plant indicated in this study correspond to the initial phase of steady-state operation. In addition, taking into account the low–medium strength of the influent, this treatment plant will be operated at higher organic loads in the following operational periods, applying different recirculation strategies. According to the initial performance, it is expected that the system will obtain organic and nitrogen removal higher than 90% working at loads of around 40 g COD/m^{2}d, 20 g BOD$_5$/m^{2}d and 12 g NH$_4$-N/m^{2}d.

With regard to the disinfection capacity, influent concentrations of TC and FC were constant at about 6.7 and 5.7 log10 MPN/100 mL, respectively (Figure 11). Significantly lower TC and FC (range of 3.8–4.0 log10 MPN/100 mL) were detected in the effluent of both VFCW and HFCW units. Moreover, at a final step, TC and FC were significantly removed after the solar-driven disinfection processes. Values of TC and FC of around 1.8 log10 MPN/100 mL were observed after AO and below the limit of detection after UV treatment. The disinfection units also help in the reduction of disagreeable tastes and odors. The AO produces residual chlorine that stays in the water even after disinfection is completed, allowing continuous safe water conditions. The UV treated effluent is stored in a tank that contains a UV lamp to avoid potential regrowth of bacteria. Other low-cost disinfection methods appropriate for low-income countries, based on solar disinfection and related processes, have already shown a great potential to address the problem of pathogens in water in regions that receive intense solar radiation (Mbonimpa *et al.* 2012; Horn *et al.* 2014; Kalt *et al.* 2014).

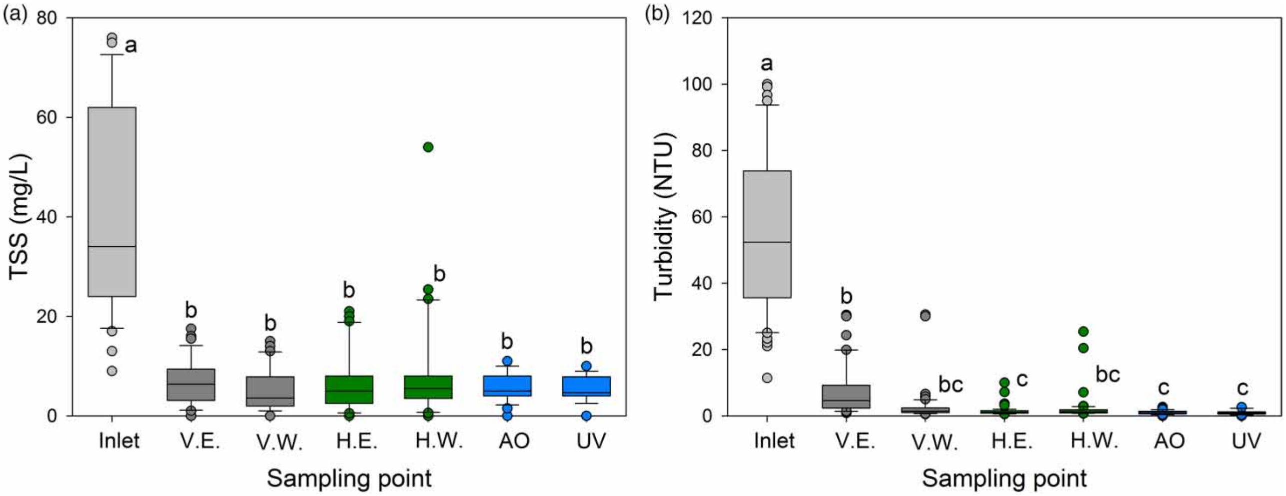

Figure 10 | TSS (a) and turbidity (b) in influent and effluent of the two vertical and two horizontal CWs and disinfection systems of AMU pilot plant. Different letters above the bars in each plot represent statistically significant differences.

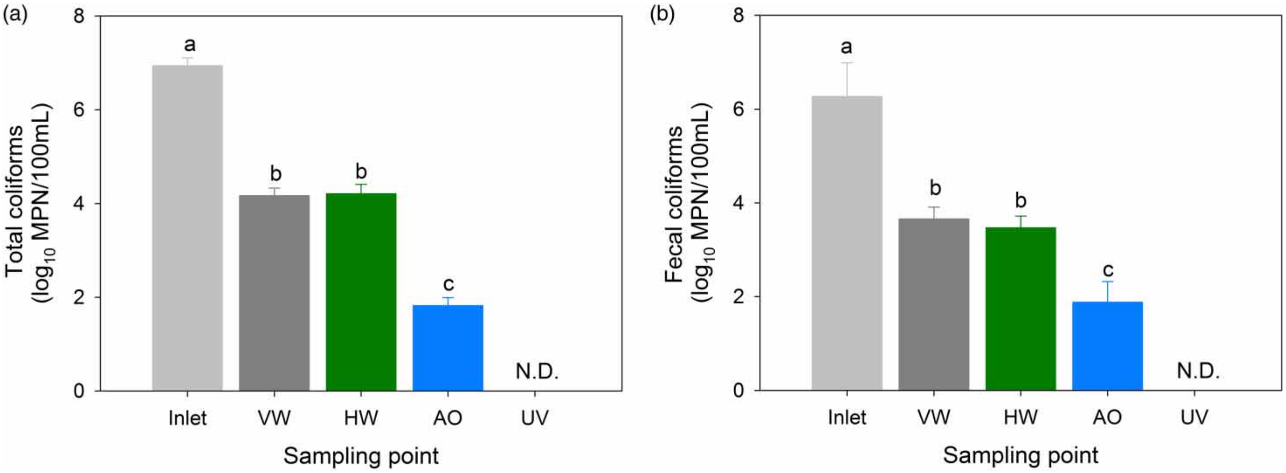

Figure 11 | TC (a) and FC (b) concentrations in the influent and effluent of west vertical and horizontal CWs and disinfection systems of AMU pilot plant. Different letters above the bars in each plot represent statistically significant differences.

The main effort for maintenance of the disinfection system comprises frequent checking on the performance and maintenance of wherever and whenever necessary (i.e. cleaning the glass cover of the UV lamp, the electrolytic cell, flow and ORP sensors, photovoltaic modules and storage tanks). An operator should spend 2 h per week at the system. Based on the recommendations of WHO on sanitary safety planning or drinking water safety planning together with the implementation of the two disinfection units, a monitoring strategy which builds on a combination of operational monitoring, compliance monitoring and verification has been designed, which ensures a continuous supply of safe water. Both the UV system and the AO system applied in this project have included on-line monitoring of the disinfection process. The two technologies stand as effective autonomous solutions to take into account in the implementation of sanitary safety and drinking water safety plans at decentralized scale.

Treatment performance of IGNTU pilot plant

Table 5 presents the different water quality parameters evaluated at IGNTU pilot plant since the system started operation. Temperature and pH along the treatment were stable and no major change was observed. DO increased

Table 5 | Water quality parameters determined at IGNTU pilot plant, where influent corresponds to the effluent from the local STP entering the horizontal flow CW, the second sampling point corresponds to the effluent of the CW, and AO effluent is the final effluent ($n = 8$)

Parameters	Influent	After CW	AO effluent
Temp (°C)	22	23 ± 0.6	24 ± 0.9
pH	8.3	8.3 ± 0.2	8.1 ± 0.2
DO (mg/L)	3	3.6 ± 0.3	8.1 ± 0.4
Alkalinity (mg/L)	66	135 ± 13	95 ± 11
Hardness (mg/L)	106	85 ± 12	27 ± 10
ORP (mV)	210	210 ± 18	408 ± 47
Conductivity (µS/cm)	1,312	882 ± 116	609 ± ±92
BOD$_5$ (mg/L)	48	35 ± 8.4	8 ± 2.4
Chlorine (mg/L)	NM	0.04 ± 0.03	0.5 ± 0.3
Nitrate (mg/L)	NM	3.0 ± 1.0	0.3 ± 1.0
Phosphate (mg/L)	NM	1.1 ± 0.5	0.2 ± 0.5

NM, not measured.

during disinfection more than 50%, thus improving the quality of the water before reuse. ORP increased in a similar proportion as a result of the higher DO availability. Alkalinity, hardness, electrical conductivity and TSS were reduced along the treatment as a result of the consumption of salts during the AO disinfection system. The production of free chlorine in the system also reduced the BOD$_5$ by around 80%. Table 5 also shows the presence of a relatively high concentration of nitrate (3.0 mg/L) that will react with the free chlorine and consume the available Cl for the disinfection. Chlorine production in the AO system reached up to 5 mg/L but was consumed by the remaining ammonia (not measured), BOD$_5$ and nitrate, reaching a break point where free chlorine was available. The measured chlorine at the effluent was 0.5 mg/L, and an increase over 1,000% is sufficient to inactivate pathogens and provide residual disinfection. Additionally, and since the removal will be affected by the contact time, the water is stored in 1 m^3 tanks before use to improve the disinfection process.

Table 6 | Pathogen indicators evaluated at the influent (after the HFCW) and effluent of the AO system ($n = 5$) at IGNTU pilot plant

Pathogen	After HFCW	AO effluent
TC	3×10^6 MPN/100 mL	BDL
FC	3×10^4 MPN/100 mL	BDL
E. coli	3×10^4 MPN/100 mL	BDL
Enterococcus	4,300 MPN/100 mL	BDL
Clostridium	1,500 CFU/100 mL	BDL
Salmonella	50 CFU/100 mL	BDL

BDL, below detection limit.

Table 6 presents pathogen indicators evaluated during the monitoring period. The tests included TC, FC, *E. coli* as well as *Enterococcus*, *Clostridium* and *Salmonella*, all required by the Indian legislation. Samples were only taken from the effluent of the HFCW and the effluent of the AO. The concentrations measured at the effluent of the HFCW show concentrations of coliforms close to raw wastewater, suggesting that the HFCW is not removing them along the treatment as would be expected. *Enterococcus* and *Clostridium* were a log-unit lower than expected in raw wastewater, also suggesting low performance of the HFCW for these indicators, while for *Salmonella* the HFCW seemed to perform better, removing up to three log-units if compared with the expected count. After the AO system, none of the target pathogens were detected. Despite this fact, the frequency and number of samples analyzed were not sufficient to guarantee the removal of pathogens, and further and continuous sampling campaigns must be carried out to ensure the safety of the treated water and no risk for the final users. Currently, the treated water is being used for irrigation of a pilot agricultural plot and green areas around the campus, and therefore pathogen removal must be guaranteed.

CONCLUSIONS AND FINAL REMARKS

The implementation of the systems under the umbrella of the SWINGS project will give the opportunity to test advanced CW configurations operating to meet local needs, under tropical conditions, using locally available materials and indigenous plants and taking advantage of local building experience. The flexibility and possibilities provided by the SWINGS pilot plants will permit the testing of different configurations and will advocate for the use of integrated treatment systems comprising UASB, CWs and solar-driven disinfection technologies in India, particularly in rural and semi-urban settings where land is relatively easily available but energy is scarce. It will also encourage counter part researchers to enrich their knowledge regarding design and operational needs.

The overall performance of AMU campus pilot plant during the first 7 months of operation at steady state shows an organic matter removal of 87% TSS, 95% BOD$_5$ and 90% COD, while Kjeldahl nitrogen removal was 89%.

The UV disinfection unit was producing water with indicator bacteria well below the concentrations indicated by the WHO, and is being used for irrigation of surrounding agricultural plots as well as toilet flushing. On the other hand, the solar-driven AO disinfection unit implemented at IGNTU campus and operated for about a year has been producing irrigation quality water for the local population.

SWINGS has enriched cooperation among the partners and after successful implementation, India may have new technological and demonstration sites that will promote the use of low-cost sustainable technologies for municipal wastewater treatment and reuse in rural areas. The low cost, flexibility and unsophisticated operation of the technologies implemented during the project constitute a promising solution to tackle the water challenge in the subcontinent.

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