Process performance and reuse potential of a decentralized wastewater treatment system

Rajiv Ranjan, Lokendra Kumar and P. C. Sabumon

ABSTRACT

The paper describes briefly the process performance and the reuse potential of a laboratory scale wastewater treatment system. The treatment involves enhanced primary treatment of Vellore Institute of Technology (VIT) campus sewage using ferric chloride as a coagulant, anaerobic digestion of coagulated organics, and biofilm aerobic process. The treated effluent after disinfection (using sunlight and chlorine) was used for irrigation of Tagetes *erecta* (marigold) plants and the plant growth parameters were evaluated for a life span of 3 months. In the primary treatment, an optimum ferric chloride dose of 30 mg/L could remove turbidity, chemical oxygen demand (COD), bio-chemical oxygen demand (BOD), and bacterial count (Escherchia Coli) of 69%, 60%, 77%, and 55%, respectively. The coagulated organics could digest in a 25 L anaerobic reactor effectively with methane content in biogas varied between 50 and 60% and enhanced volatile suspended solids (VSS) reduction up to 70%. Sunlight based photo-oxidation followed chlorine disinfection saved 50% of the chlorine dose required for disinfection and treated effluent was fit for reuse. The results of growth parameters for Tagetes *erecta* plants indicate that anaerobically digested sludge is an excellent soil conditioner cum nutrient supplier. The results of this study exhibit a promising reuse potential of a decentralized wastewater treatment system and needs to be promoted for field scale applications.

Key words | anaerobic digestion, biofilm aerobic process, decentralized wastewater treatment, reuse, tagetes *erecta* plants

Rajiv Ranjan
Lokendra Kumar
P. C. Sabumon (corresponding author)
School of Mechanical & Building Sciences,
Vellore Institute of Technology (VIT),
Chennai Campus, Chennai 600 127, Tamilnadu,
India
E-mail: *pcsabumon@vit.ac.in*

INTRODUCTION

In the present 21st century, the water crisis is hitting many parts of the world in terms of quantity and quality as a result of improper planning and development. Water usage is growing at double the rate of population increase, therefore paradigm shifts based on holistic management (to maximize use and recovery of water, energy, nutrients, and materials) are needed (UNEP 2012). To overcome these challenges, one of the best options is to look the wastewater as a resource and change the philosophy of wastewater treatment and disposal from a linear nature to a cyclic nature. Therefore, on an urgent basis, the traditional linear treatment systems must be transformed into the cyclical treatment to promote the conservation of water and nutrient resources and thereby increase the scope of sustainability of wastewater treatment practice. For this development of an appropriate decentralized wastewater treatment system is especially essential and to use it in developing countries to meet their sanitation needs in a sustainable route.

Goal 6 of the United Nations Sustainable Development Goals ('Clean Water and Sanitation') foresees achieving access to adequate and equitable sanitation and hygiene for all by 2030 and, within the same time frame, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally. Still, around 1.8 billion people globally use sources of drinking water that are fecally contaminated, over 1.7 billion people currently live in river basins where water use exceeds recharge, and more than 80% of wastewater from human activities is discharged without any treatment (UNDP 2017). Risch *et al.* (2015) conducted a life cycle assessment of conventional (gravity) urban wastewater systems based on a detailed component inventory, including construction and operation of both sewers and wastewater treatment plants (WWTPs). Results showed that the construction of sewer infrastructures themselves has, alone, an environmental impact on many of the considered categories that

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is larger than both: the construction and the operation of the WWTPs. Therefore, to meet the Goal 6 of United Nations Sustainable Development Goals in a sustainable way, promotion of decentralized WWTPs is the need of the present time, especially in developing countries. Decentralized wastewater management is used to treat and dispose, at or near the source, relatively small volumes of wastewater, originating from single households or groups of dwellings located in relatively close proximity (indicatively, less than 3–5 km, maximum) and not served by a central sewer system connecting them to a regional WWTP. It has been claimed that decentralized wastewater treatment systems favor water recycling and reuse in proximity of their location (Opher & Friedler 2016). Other resources that can be readily recycled are: bio-energy (mostly from the organic material transformation), and nutrients, mainly nitrogen and phosphorus (Van Loosdrecht & Brdjanovic 2014). Also, in these cases, local reuse of recovered components helps to form 'closed loops' of resource uses, in line with the principles of 'circular economy'.

The available decentralized wastewater treatment systems are septic tanks, constructed wetlands, membrane bioreactors, and upflow anaerobic sludge blanket (UASB) reactors. There are merits and demerits in each of these systems for decentralized wastewater treatment (Capodaglio 2017). Therefore, an alternative decentralized treatment system for sewage treatment is essential to overcome some of the demerits of available treatment systems. In conventional wastewater treatment, the primary treatment removes the large and settliable solids by physical separation to an extent of 50–60% with corresponding bio-chemical oxygen demand (BOD) removal of 30–35% and the remaining suspended solids and colloidal solids enter into next stage biological treatment process (Metcalf & Eddy 2001). The degradation of these suspended solids and colloids in biological treatment process takes more time at an extreme level of energy input (in aerobic process) and /or reactor volume (in anaerobic process) depending on the respiratory mode of biological treatment process. There is a better option of treating wastewater by an enhanced primary treatment with removal of colloids and settliable solids by chemical coagulation using ferric chloride ($FeCl_3$) as a coagulant. The concentrated coagulated organics can be separated easily and treated anaerobically with a lot of advantages. The supernatant of the primary treatment, which contains mainly soluble organics, can be treated in an aerobic fixed film reactor in an efficient and cost effective way. Finally, sunlight could be employed for partial disinfection thereby saving disinfectant requirement before reusing the water for irrigation. Such an easy and adaptable process change to the conventional treatment process can promote decentralized wastewater treatment for communities, apartment complexes/blocks, small towns, isolated resorts, and in campuses of institutions like Vellore Institute of Technology (VIT).

The aim of this paper is to discuss briefly the process performance of a laboratory scale wastewater treatment system suitable to adopt in a decentralized mode and the possibility to make use of the products of treatment for the benefits of local communities. The start-up of the biological processes was done using locally available mixed bacterial consortiums. The results of this study demonstrate an ecologically sustainable and cost effective wastewater treatment system in support of the circular economy. For example, most of the organic carbon from wastewater was conserved during enhanced primary treatment and recovered later as biogas (energy) during anaerobic digestion. The effective BOD removal of the carried-over organic carbon is achieved in 3 h during secondary treatment at minimum input of energy at a higher organic loading rate (OLR) of 3 kg COD/m^3/d with the conservation of N and P present in wastewater for reuse in irrigation. Moreover, the system did not produce excessive sludge from the aerobic process, thereby avoiding sludge treatment and disposal issues; rather, the sludge produced from the anaerobic digestion could be used as a soil conditioner and nutrient supplier. The freely available sunlight has also been made use of to reduce the cost of disinfection of treated wastewater before its reuse.

MATERIALS AND METHODS

Wastewater and its characterization

VIT Vellore campus sewage was taken from the equalization tank of VIT sewage treatment plant (Latitude 12°58′9.12″ N & Longitude 79°09′21.24″ E), Vellore district, Tamil Nadu, India, and analyzed for parameters such as pH, turbidity, COD, BOD, suspended solids (SS), total solids, TKN, NH_4-N, total phosphorous and bacterial count (E-Coli) as per Standard Methods (APHA 1998).

Schematic of decentralized wastewater treatment system

The schematic of the decentralized lab-scale wastewater treatment system studied is shown in Figure 1.

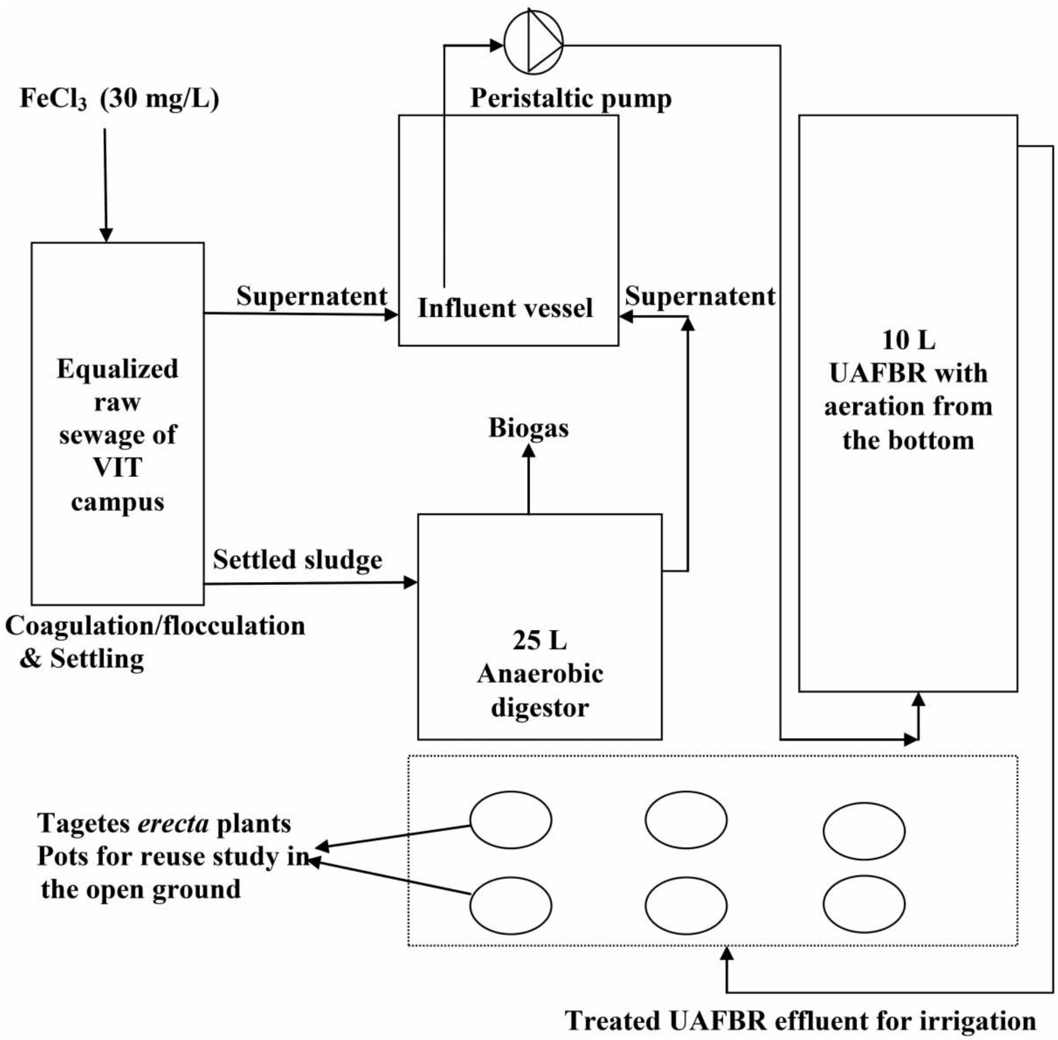

Figure 1 | The schematic of the lab-scale decentralized wastewater treatment system.

Enhanced primary treatment

The fresh sewage (30 L) was collected in a plastic bucket of 50 L capacity (30 cm bottom internal diameter with 75 cm height) from the equalization tank of VIT's WWTP and brought to the Environmental Engineering Laboratory of VIT, Vellore campus. The sewage was then stirred rapidly (manually using wooden reaper) and 30 mg/L of $FeCl_3$ was dosed, and stirring continued for another minute. Then, the contents of the bucket were slowly mixed manually using a broom of coconut tree leaf (to create a suitable velocity gradient for effective flocculation) for 20 minutes and thereafter settling of flocs was allowed for 30 minutes. Then, the supernatant was transferred to the influent vessel of the Upflow Aerobic Fixed Bed Reactor (UAFBR) and settled sludge was transferred to an anaerobic digester of 25 L capacity. The supernatant was analysed for pH, turbidity, total suspended solids, total solids, COD, BOD, TKN, NH_4-N, total phosphorous and bacterial count (E-Coli) to evaluate the performance of primary treatment.

Upflow aerobic fixed bed reactor operation

The UAFBR of 10 L liquid capacity (120 cm height × 10 cm × 10 cm) was made using 6 mm thick acrylic sheet. Polyvinyl chloride (PVC) rings (19 mm outer diameter and 20 mm height) having a porosity of 90% and bulk density of 154 kg/m^3 were used as the attachment media for microbes. A peristaltic pump (Miclins, India) was used for feeding wastewater to the UAFBR from the influent vessel. The start-up of the UAFBR was done by recycling of wastewater (fresh sewage with 20% activated sludge on a volume basis) from the influent vessel for biofilm growth over the PVC rings for 2 weeks. The aeration of the UAFBR was done by compressed air supplied at the bottom of the reactor through a diffuser stone. After 2 weeks of recycling operation, the UAFBR was started in continuous operation at 24 h hydraulic retention time (HRT) and the HRT further reduced to increase the OLR after the stabilized operation in each HRT. The HRTs studied were 12 h, 6 h, 3 h, 1.5 h, and 1 h. The dissolved oxygen was maintained in the range of 2–4 mg/L and temperature varied from 26 °C to 31 °C in the UAFBR during the study over a period of 4 months. The supernatant from the UAFBR was analysed for pH, turbidity, total suspended solids, total solids, COD, BOD, TKN, NH_4-N, total phosphorous and bacterial count (E-Coli) to evaluate its performance.

Anaerobic digester operation

The start-up of the anaerobic digester was done by seeding 10 L anaerobically digested cow dung slurry (having volatile suspended solids of 92.7 g/L) and 1.5 L of settled sludge (coagulated organic sludge). Anaerobic digested cow dung slurry, as the seed biomass for a mixed culture bacterial population for anaerobic digestion, was obtained from an active local domestic Gobar gas plant. After 10 days, 1.5 L of supernatant was taken out daily and 1.5 L of settled sludge was fed to the digester. After stabilization of the process, the HRT of the operation was reduced from 10 days to 7 days. The biogas was collected through the liquid-displacement method. The supernatant from the anaerobic digester was fed to the UAFBR after mixing with the supernatant from the enhanced primary treatment. The supernatant was analysed for pH, volatile fatty acids (VFA), bicarbonate alkalinity and soluble COD.

Chlorination of UAFBR effluent

Eight BOD bottles were filled, with 200 mL of UAFBR effluent in each bottle. Varying doses of chlorine of 10, 20, 30, 40, 50, 60, 80, and 100 mg/L were added to each bottle. The selected dose was added from the stock solution of chlorine (prepared using bleaching powder) after determining its strength. The bottles were closed and were shaken in an orbital shaker (Remi, India) at 120 rpm for 30 min. After 30 min, the samples from each bottle were analyzed for residual chlorine, pH, and bacterial count. A control bottle was also kept in similar conditions without any chlorine dose.

Photo-oxidation followed by chlorination of UAFBR effluent

UAFBR effluent was taken in a clean plastic bucket for photo oxidation at varying depths of water of 10, 15, and 25 cm. The effluent was exposed to the direct sunlight for 3 h/day at each depth during Indian standard time 11.00 h to 14.00 h when the intensity of sunlight was maximum (120,000–140,000 Lux) at VIT, Vellore campus, and samples were drawn for bacterial count. After photo oxidation, samples were subjected to chlorination at different chlorine doses of 5, 10, 20, 30, 40, and 50 mg/L in the same way as described in the previous section.

Reuse of treated wastewater

To investigate the reuse potential of treated water for irrigation, Tagetes *erecta* saplings obtained from VIT's nursery were used in field conditions (in an outdoor environment closer to the laboratory). Tagetes *erecta* was selected because its life span is 3–4 months and was suitable for the study season (January to April). Also, Tagetes *erecta* is one of the commercial flowers (Marigold) in India used for decoration on various occasions. There was no artificial fertilizer used during the growth period; that is, from germination to the end of the plants' life. Tagetes *erecta* plant saplings each having the same features were transferred to four different pots having red soil in which to grow the plant. The number of Tagetes *erecta* plants in each pot was 10. Different types of water were used for the irrigation of the Tagetes *erecta* saplings in pots. They are: Tap water (tagged as Control S1), UAFBR effluent (as S2), UAFBR effluent after chlorination (as S3), UAFBR effluent after photo oxidation followed by chlorination (as S4), and anaerobic digester supernatant (as S5). During the morning and the evening, 300 mL of designated water was irrigated into each set of plants. The growth of each plant was monitored by measuring different parameter such as length of plant, root length, shoot length, stem perimeter, number of leaves, area of leaves, number of flowers, and chlorophyll content. Another set of plant saplings was used to study the use of digested sludge as a soil conditioner-cum-nutrient. For this, one liter of anaerobic digested sludge was mixed with 4 kg of red soil and 10 Tagetes *erecta* saplings were planted in a pot filled with conditioned soil (as S6). UAFBR effluent was used to irrigate the plants (except S1 and S5) and the growth of the plants was monitored for listed parameters for comparison. S1 to S6 had sufficient number of saplings (30% extra) for the growth parameter analyses at varying time intervals.

Analytical techniques

All physico-chemical and bacteriological analysis was carried out as per Standard Methods (APHA 1998). Volatile fatty acids (VFA) and bicarbonate alkalinity of anaerobically treated effluent was determined as per the procedure developed by Anderson & Yang (1992). The composition of CH_4 in biogas was determined by using Orsat apparatus. A measured volume of gas is scrubbed first through a solution of 30% potassium hydroxide (KOH) to remove CO_2. The biogas is assumed to be composed of only CH_4 and CO_2. After scrubbing, the volume of gas remaining was considered to be CH_4 and the percentage of CH_4 was determined. Chlorophyll content of Tagetes *erecta* leaves was determined by extraction in 80% acetone (10 mg plant material extracted in 1 mL of acetone) and the absorption of extract at 663 nm and 645 nm was measured in a spectrophotometer. Using the absorption coefficients, the amount of chlorophyll was calculated using the following equations:

$$\text{mg chlorophyll } a/\text{g tissue} = 12.7\ (A_{663}) - 2.69\ (A_{645})V/(1000\,W) \quad (1)$$

$$\text{mg chlorophyll } b/\text{g tissue} = 22.9\ (A_{645}) - 4.68\ (A_{663})V/(1000\,W) \quad (2)$$

$$\text{mg Total chlorophyll}/\text{g tissue} = 20.2\ (A_{645}) + 8.02\ (A_{663})V/(1000\,W) \quad (3)$$

where A = absorbance at specific wavelengths, V = final volume of chlorophyll extract in 80% acetone, W = fresh weight of tissue extracted.

RESULTS AND DISCUSSION

The profile of the wastewater characteristics

Table 1 shows the wastewater characteristics before and after treatment. The composition of raw sewage varies from place to place because it depends on the habits of the population. From the characteristics of VIT's sewage, it was found that all parameter values were in the range of medium strength sewage in India (Garg 1998).

Table 1 | Wastewater characteristics before and after treatment

Parameter	Raw sewage	After enhanced primary treatment	Treated water from UAFBR
pH	7.22–7.46	7.12–7.20	7.10–7.90
Turbidity (NTU)	80–130	40–70	4–6
COD (mg/L)	384–640	160–224	32–64
BOD (mg/L)	156–200	60–110	6–30
Total suspended solids (mg/L)	300–780	100–280	20–40
Total solids (mg/L)	1,820–2,150	1,490–1,570	620–970
Bacterial count ($\times 10^6$) (CFU/mL)	16.5–19.5	1.9–6.1	1.4–5.1
TKN (mg/L as N)	35–40	25–30	10–40
Total phosphorous (mg/L as PO_4-P)	22–32	20–30	10–25
Ammonical nitrogen (mg/L as N)	10–15	10–15	10–40

Note: Fecal Coliforms and helminth eggs are not analysed.

Enhanced primary treatment

The parameter values (Table 1) after the primary treatment show the enhanced performance compared to conventional treatment. In the primary treatment, an optimum ferric chloride dose of 30 mg/L could remove turbidity, COD, BOD and bacterial count (E-Coli) amounts of 69%, 60%, 77% and 55%, respectively. Normally, the conventional treatment removes 40–50% suspended solids and 30–35% BOD. Fenton's reagent dose of 30 mg/L during coagulation-flocculation of combined wastewater gave a comparable COD removal of 57% (Duran *et al.* 2003). The results showed enhanced removal of COD/BOD/bacterial count in primary treatment as a result of the $FeCl_3$ addition as a coagulant.

Operation of anaerobic digester

Figure 2 shows the weekly performance during operation of the 25 L capacity anaerobic digester. From Figure 2(a), performance values indicated that the anaerobic digestion of sludge improved with time of operation. After 8 weeks of operation, the COD of anaerobic effluent was below 100 mg/L. The variation in the biogas production might be due to variation of the feed COD to the digester. The percentage of methane in the biogas was varied from 50 to 60%. The biogas was tested as flammable through a Bunsen burner and therefore could be used as a cooking fuel in

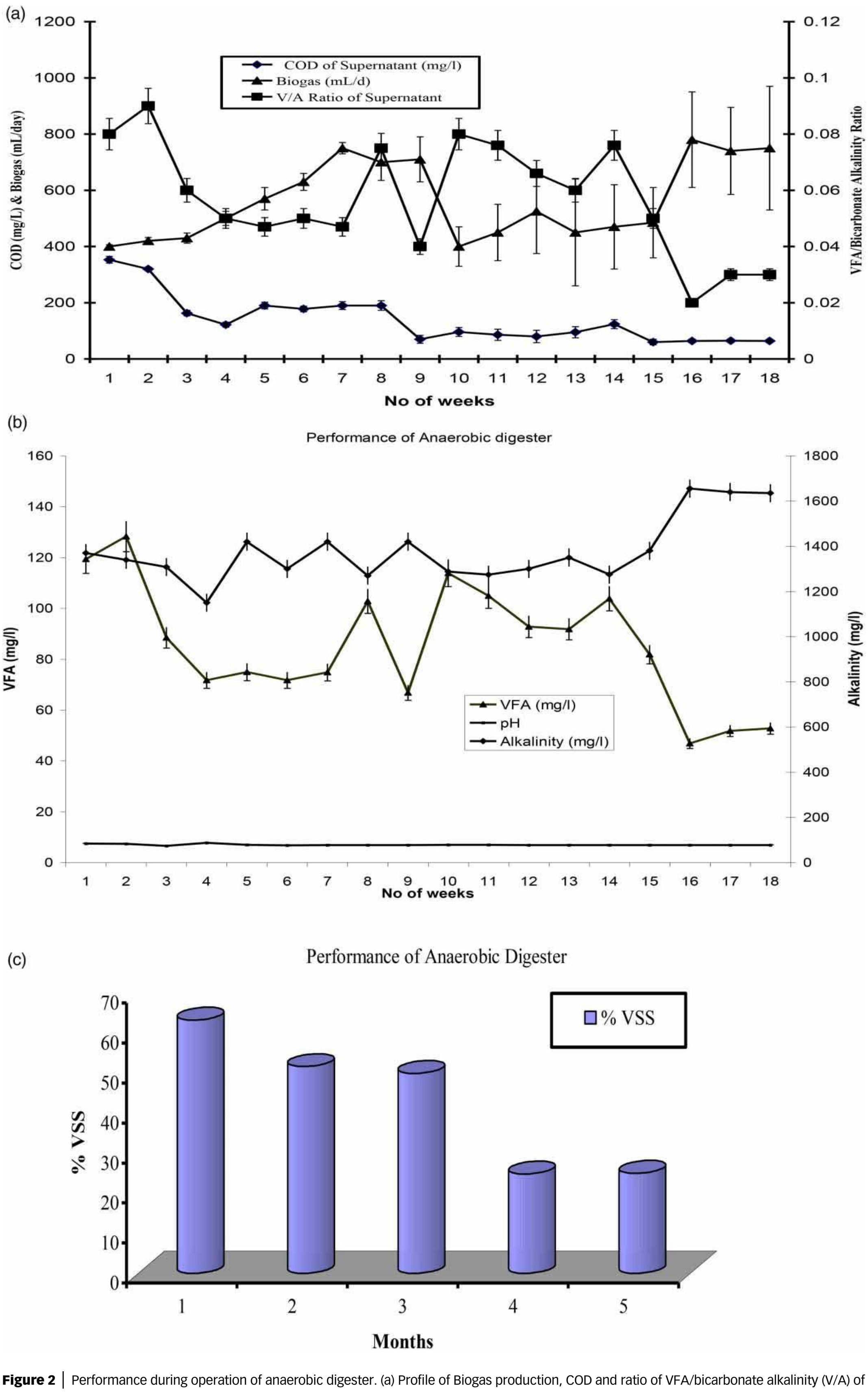

Figure 2 | Performance during operation of anaerobic digester. (a) Profile of Biogas production, COD and ratio of VFA/bicarbonate alkalinity (V/A) of digester effluent. (b) Profile of VFA, pH and alkalinity in the digester. (c) Profile of percentage VSS in the digester with time of operation.

the locality. Process parameters like pH (6.9–7.4), VFA (22–110 mg/L), bicarbonate alkalinity (600–1,700 mg/L) (Figure 2(b)) and VFA/bicarbonate alkalinity ratio were within the limits of safe operation of the anaerobic digester. The low ratio of VFA/alkalinity (<0.3) indicates that anaerobic digestion was effective in the reactor (Yacob *et al.* 2006; Risk *et al.* 2007). Aqueous sulphides and total iron in anaerobic effluent varied in the range of 14–19 mg/L and 0.5–1 mg/L respectively. This could be due to precipitation of iron sulphides in the digester and thereby controlling the odor emission from the digester. Park & Novak (2013) added $FeCl_3$ as a beneficial additive for odor mitigation from the sludge digestion of sewage treatment plant sludge. The temperature of the anaerobic digester varied from 34 °C to 39 °C. Methane forming bacteria grow best in the mesophilic temperature range between 35 and 40 °C (Grasius *et al.* 1997) and therefore the anaerobic digester was operated in optimal temperature.

It was observed that the percentage volatile fraction of digested sludge was decreased with time of operation from initial values of 65.2–68.4 to lower values of 22.8–25.6 at the end of the study (Figure 2(c)). Therefore, the presence of Fe^{3+} in the digester has increased the sludge stabilization performance. Similar results are reported by Park & Novak (2013). The digested sludge had good settling and dewatering properties and thereby further reduced the operational cost involved in the de-watering of digested sludge. In short, the ferric coagulated sludge from the primary treatment could be digested very efficiently in the anaerobic digestion process with biogas recovery and the process reduces the overall cost involved in the sludge handling.

Operation of UAFBR

Figure 3 shows the performance of UAFBR operations in BOD removal. The treated effluent BOD was less than 10 mg/L and maintained 82–96% reduction in BOD at steady state of operation. The performance of the reactor affected at above 3 kg COD/m^3/day (results not shown). However, the COD of the effluent remained less than 100 mg/L at higher OLR of 4 kg COD/m^3/day. The percentage removal of suspended solids in the UAFBR varied from 72 to 86% with concentrations of less than 100 mg/L. Whenever there was a change of OLR, the reactor performance decreased and regained normal performance within a short time. At steady state operation, the effluent from the UAFBR had a pH (7.1–7.9), turbidity (4–6 NTU), suspended solids (20–40 mg/L), BOD (6–10 mg/L), COD (32–64 mg/L), NH_4-N (10–40 mg/L), TKN (10–40 mg/L), and phosphorus 10–25 mg/L (Table 1). McDowell & Hubbell (2001) reported that submerged fixed film reactor technology can be employed for effective wastewater treatment with high biomass retention. In this study, the efficient performance was obtained due to the fact that more of the soluble fraction of the organic matter was fed to the reactor unlike in conventional treatment. Moreover, due to the attachment and/or trapping of biomass in the packing media, there was no need for intense aeration to keep the biomass in suspension. The aeration requirement is just to oxidize the BOD in less HRT and thus preventing the oxidation of NH_4-N. Therefore, whenever the treated effluent is intended for irrigation, this type of reactor is very effective for BOD removal.

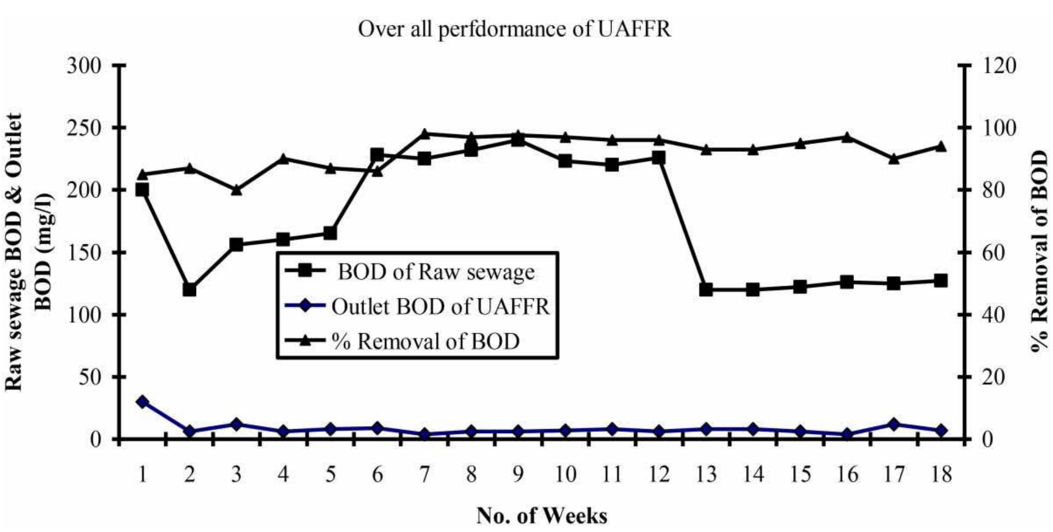

Figure 3 | Performance of UAFBR operation in BOD removal. (UAFFR in figure denotes UAFBR).

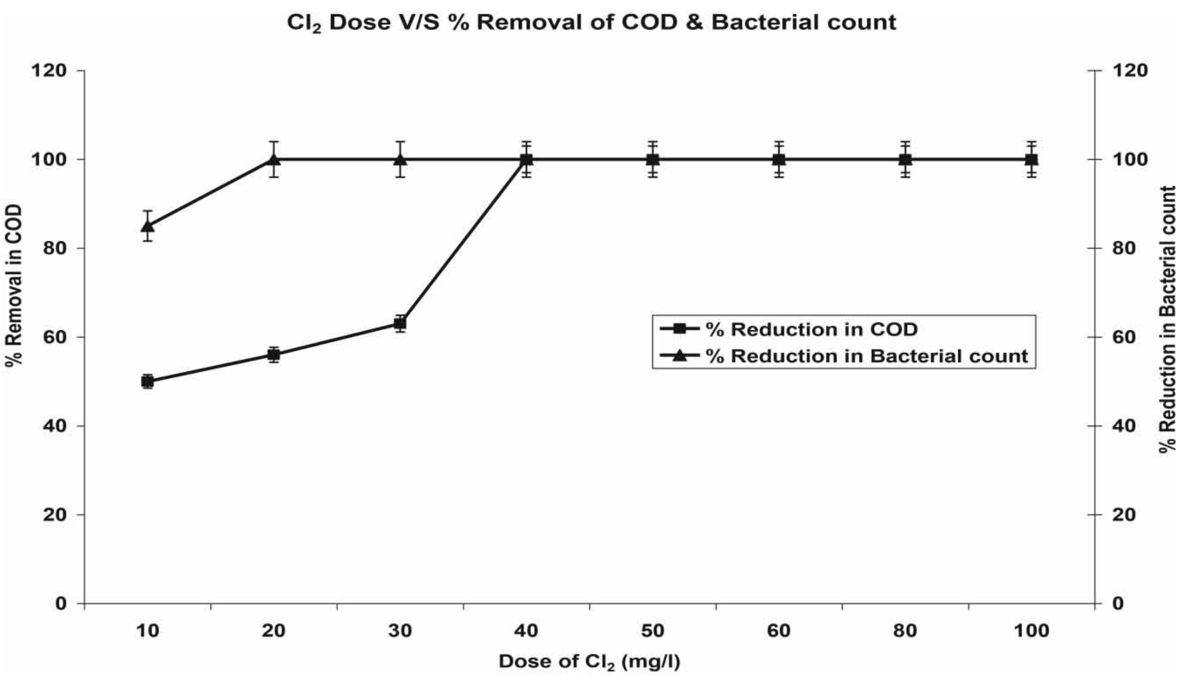

Figure 4 | Results of chlorination of UAFBR effluent.

Chlorination of UAFBR effluent

The treated effluent from the UAFBR contained bacteria in the order of 10^6 CFU/mL. Before reuse of treated effluent, disinfection of the pathogen is necessary because it can affect human health. So UAFBR effluent was studied for disinfection of pathogens by break point chlorination and photo oxidation followed by chlorination. At a chlorine dose of 40 mg/L, breakpoint was achieved and treated water was free from any bacterial count and organic matter (Figure 4). If bacterial disinfection is only to be attained, a dose of 20 mg/L is sufficient. After breakpoint chlorination, treated water was suitable for irrigation (WHO 1989). Mujeriego *et al.* (2000) reported that wastewater treated by the conventional activated sludge process needs 25–45 mg Cl_2/L for chlorination and after chlorination, it had fecal coliforms and fecal streptococci concentrations lower than 100 CFU/100 mL. The results of the present study were better than their results.

Disinfection of UAFBR effluent by photo-oxidation followed by chlorination

As a result of photo oxidation of treated water, there was a reduction of 10^3 CFU/mL in bacterial count at all the depths of water studied (Table 2). The breakpoint was achieved at a chlorine dose of 20 mg/L with no bacterial count after 30 min. contact time. The residual chlorine at breakpoint was 2.1 mg/L. The results show that after photo-oxidation chlorine demand was decreased by a factor of 2. Therefore, photo-oxidation followed by chlorination appears to be an alternative economical method of disinfection for treated water. In decentralized field application, the treated water could be kept in a shallow tank

Table 2 | Results of photo oxidation followed by chlorination of UAFBR effluent

Parameter	Average value of bacterial count (CFU/mL) after photo oxidation	Dose of chlorine (mg/L)	Average value of bacterial count (CFU/mL) after chlorination
		5	$(72 \pm 35)\ 10^3$
Photo oxidation in 4 inches depth	$(27 \pm 5.2)\ 10^3$	10	416 ± 158
Photo oxidation in 5 inches depth	$(32.5 \pm 5.6)\ 10^3$	20	Absent
Photo oxidation in 10 inches depth	$(49 \pm 13.2)\ 10^3$	30	Absent

UAFBR effluent bacterial count: $(5.3 \pm 4.1) \times 10^6$ CFU/mL, Number of samples = 3, Time of exposure for photo oxidation = 3 h, Contact time for chlorination = 30 min.

or pond for sunlight exposure and then later subject to chlorination or any other disinfection methods (UV, ozonation). This can reduce around 50% of the cost involved in the disinfection process and make the wastewater treatment more sustainable by using the power of sunlight.

Reuse of treated wastewater

The growth parameters (both visible and invisible) of all the Tagetes *erectas* are shown in Tables 3 and 4. In respect of the tap water irrigated sample (S1), all other plant samples (S2 to S6) showed improved growth parameters. It has been

Table 3 | Plant growth parameters (Visible) after irrigation using different types of water samples

Type of water sample for irrigation	Number of days of growth	Plant height (cm)	Root length (cm)	Shoot length (cm)	Stem periphery (mm)	Number of branches	Number of leaves	Leaf area (cm^2)	Number of flowers
Tap water- Control (S1)	0	9	4	5	3	0	20	2.3	0
	15	12.0	5	7	4	1	46	5.5	0
	30	15.5	5.5	9.5	4	3	104	15.0	1
	45	23	7	16	5	3	243	56.7	4
	60	25	7	18	7	4	259	58.3	8
	75	26	7	19	7	4	270	69.4	2
	90	28	7	21	7	6	320	80.2	2
UAFBR effluent (S2)	0	9	4	5	3	0	22	2.4	0
	15	12.5	6	6.5	4	1	48	6.0	0
	30	16.5	6.5	10	5	4	115	20.0	2
	45	25	7	18	5	5	418	81.3	6
	60	28	8	20	6	5	450	95.4	7
	75	30	8.5	21.5	6	6	463	102.5	8
	90	35	8.5	26.5	6	6	475	108.5	2
UAFBR effluent after chlorination (S3)	0	9.5	4	5.5	3	0	20	2.3	0
	15	12.5	6	6.5	4	1	47	6.10	0
	30	17	6	11	4	4	120	23.4	2
	45	27	7	20	5	5	425	129.0	4
	60	29	8	21	6	5	435	138.0	6
	75	32	8	24	6	6	440	140	5
	90	35	8	27	6	6	460	144	2
UAFBR effluent after photo oxidation followed by chlorination (S4)	0	9	4	5	3	0	20	2.1	0
	15	13	6	7	4	1	49	6.2	0
	30	16.5	6	10.5	5	4	126	24.3	2
	45	25	9	16	6	5	400	130.7	4
	60	30	9	22	6	6	435	160.3	**10**
	75	35	9	26	6	6	460	190.3	6
	90	36	9	28	7	7	**500**	**210.3**	2
Anaerobic digester supernatant (S5)	0	9.5	4	5.5	3	0	**23**	**2.3**	0
	15	15	6	9	5	1	**58**	**6.8**	0
	30	19	7	12	6	5	**153**	**26.5**	3
	45	27	7	20	10	7	**424**	**132.6**	6
	60	30	7	23	11	7	**528**	**198.3**	**10**
	75	36	7	29	11	10	**578**	**276.2**	4
	90	38	8	30	12	10	**618**	**299.3**	2
Anaerobic digester sludge amended soil pot and UAFBR effluent (S6)	0	9	4	5	3	0	**20**	**2.2**	0
	15	15	6	8.5	5	0	**58**	**6.8**	0
	30	19	7	12	6	4	**150**	**26.0**	3
	45	27	6	21	9	5	**412**	**130.0**	5
	60	32	7	25	11	6	**513**	**187.5**	5
	75	36	7	29	11	7	**568**	**255.2**	4
	90	38	8	30	12	8	**612**	**289.3**	1

Table 4 | Plant growth parameters (Invisible) after irrigation using different types of water samples

Type of water sample for irrigation	Number of days of growth	Fresh weight of root (g)	Fresh weight of shoot (g)	Dry weight of root (g)	Dry weight of shoot (g)	% Moisture in root	% Moisture in shoot	Chlorophyll A (mg/g tissue)	Chlorophyll B (mg/g tissue)	Total chlorophyll (mg/g tissue)
Tap water-Control (S1)	0	0.02	0.16	0.003	0.021	85	86	0.06	0.032	0.092
	15	0.04	0.26	0.009	0.041	75	84	0.177	0.092	0.269
	30	0.06	0.69	0.023	0.135	62	80	0.105	0.289	0.394
	45	0.31	2.58	0.071	0.390	77	85	0.175	0.345	0.520
	60	0.33	3.22	0.075	0.411	77	87	0.188	0.351	0.539
	75	0.36	3.63	0.075	0.420	79	88	0.195	0.381	0.576
	90	0.38	3.31	0.080	0.450	78	89	0.202	0.412	0.614
UAFBR effluent (S2)	0	0.01	0.12	0.003	0.022	70	82	0.080	0.048	0.128
	15	0.04	0.28	0.009	0.052	78	81	0.246	0.153	0.399
	30	0.08	1.19	0.043	0.209	48	83	0.291	0.252	0.544
	45	0.35	4.48	0.094	0.650	73	85	0.185	0.369	0.544
	60	0.35	5.00	0.098	0.691	72	86	0.301	0.373	0.674
	75	0.36	5.01	0.098	0.751	73	85	0.307	0.441	0.748
	90	0.37	5.04	0.100	0.762	73	84	0.310	0.491	0.801
UAFBR effluent after chlorination (S3)	0	0.01	0.09	0.001	0.009	90	90	0.010	0.051	0.061
	15	0.04	0.29	0.009	0.054	78	81	0.247	0.153	0.400
	30	0.08	1.20	0.042	0.204	50	83	0.291	0.222	0.513
	45	0.37	4.10	0.081	0.640	78	84	0.194	0.363	0.557
	60	0.38	4.50	0.093	0.652	75	85	0.295	0.336	0.631
	75	0.39	4.75	0.094	0.691	75	85	0.310	0.314	0.624
	90	0.40	5.02	0.131	0.720	66	86	0.320	0.314	0.661
UAFBR effluent after photo oxidation followed by chlorination (S4)	0	0.02	0.10	0.001	0.010	95	89	0.050	0.027	0.077
	15	0.04	0.30	0.010	0.055	77	81	0.248	0.161	0.409
	30	0.08	1.19	0.040	0.200	51	83	0.292	0.252	0.544
	45	0.41	4.14	0.114	0.650	72	84	0.292	0.363	0.655
	60	0.42	4.61	0.123	0.661	71	86	0.301	0.368	0.669
	75	0.42	4.76	0.141	0.678	73	86	0.333	0.428	0.761
	90	0.44	5.03	**0.149**	0.720	68	86	0.361	0.463	**0.824**
Anaerobic digester supernatant (S5)	0	0.02	0.13	**0.003**	**0.014**	85	89	0.029	0.015	**0.044**
	15	0.05	0.40	**0.013**	**0.058**	73	85	0.032	0.562	**0.594**
	30	0.10	1.29	**0.041**	**0.201**	59	30	0.301	0.602	**0.903**
	45	0.36	4.27	**0.113**	**0.686**	68	83	0.306	0.605	**0.911**
	60	0.36	4.29	**0.121**	**0.694**	66	84	0.309	0.621	**0.930**
	75	0.42	5.33	**0.134**	**0.698**	68	86	0.321	0.664	**0.985**
	90	0.42	5.41	**0.161**	**0.731**	65	86	0.359	0.673	**1.032**
Anaerobic digester sludge amended soil pot and UAFBR effluent (S6)	0	0.02	0.11	0.002	0.012	90	89	0.025	0.013	**0.038**
	15	0.04	0.41	0.012	0.058	72	86	0.134	0.476	**0.610**
	30	0.10	1.29	0.040	0.200	60	84	0.299	0.601	**0.900**
	45	0.34	4.27	0.112	0.650	67	84	0.301	0.621	**0.922**
	60	0.35	4.28	0.123	0.694	65	84	0.334	0.663	**0.997**
	75	0.40	5.29	0.133	0.697	66	87	0.371	0.674	**1.045**
	90	0.45	5.40	0.159	0.720	65	87	0.385	0.681	**1.066**

observed that the chlorinated water irrigated sample (S3) was experiencing an adverse effect on the number of leaves, leaf surface area, number of flowers and its chlorophyll content compared to anaerobic digestor supernatant irrigated plant (S5) and soil amended plant (S6) with anaerobically digested sludge (highlighted figures). This could be because of additional nutrients available to these sets of plants, especially N, P and K along with the supernatant and digested sludge. The chlorophyll content in the latter case is 40% and 38% greater respectively. By comparing UAFBR effluent irrigated plants (S2) with soil amended plants (S6), all the growth parameters of S6 showed better values and that shows that the anaerobic digested sludge is an excellent soil conditioner-cum-nutrient rich agent.

However, the presence of helminth eggs was not analysed in this study and before real field-scale application the sludge quality would need to be checked as per the prevailing standards for such cases. Among the UAFBR effluent irrigated plants (S2 to S4), there was not much significant change in the growth parameters (except the chlorophyll content in S3). However, photo oxidation followed by chlorinated water is better for the re-use because of the absence of pathogens and therefore is no risk to human or animal contact and growth parameters were among the best (highlighted).

Up to 60 days, the plant growth was very high in the entire samples studied and after that rate of plant growth decreased. After 75 days, flowering decreases, because it is a seasonal plant having a life span of 3–4 months. The maximum number of flowers observed in S4 and S5. Therefore, wherever agricultural fields are available, anaerobic supernatant could also be used for irrigation to increase the productivity of non edible crops. It is to be noted that above limited data analysis was done based on a single set of data of each parameter and therefore the statistical significance of the data is not interpreted.

CONCLUSIONS

This study demonstrates the possibility of a cost-effective decentralized wastewater treatment system which can be either adapted to the existing wastewater treatment plants and/or to design a new WWTP. The wastewater is being considered as a resource and attempts were made to recover the energy, nutrients and water, which could be used for the sustainable development of the locality. Such an approach is the need of the hour for promoting wastewater treatment in developing countries to achieve Goal 6 of the United Nations Sustainable Development Goals ('Clean Water and Sanitation').

From the results of this investigation, the following conclusions can be drawn:

- Ferric chloride dose of 30 mg/L could enhance the turbidity, COD, BOD and bacterial count removals in the primary treatment of sewage.
- Coagulated organics could be digested anaerobically in an effective way with the possibility of biogas utilization and digested sludge as soil conditioner-cum-nutrient supplier.
- Upflow aerobic fixed bed reactor (UAFBR) could treat the soluble organics in wastewater effectively at 3 h HRT and at higher OLR (3 kg COD/m^3/d).
- The photo oxidation could reduce the chlorine dose for disinfection by 50%.
- The treated effluent from the UAFBR was suitable for irrigation after photo-oxidation followed by disinfection.

Overall, the results of this study show a promising reuse potential of treated water and other products like biogas and digested sludge. Therefore the field scale application of such wastewater treatment system is recommended for decentralized application.

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