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Wastewater renovation using constructed soil filter (CSF): A novel approach

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ABSTRACT

Constructed soil filter (CSF) also known as *Soil Biotechnology* (SBT) is a process for water renovation which makes use of formulated media with culture of soil macro- and microorganisms. CSF combines sedimentation, infiltration and biodegradation processes to remove oxidizable organics and inorganics of wastewater in a single facility. Operating experience shows hydraulic loading in the range of 0.05–0.25 m^3/m^2 h and organic loading up to 200–680 g/m^2 d. The results show increase in dissolved oxygen levels, COD removal (from 352 mg/l to 20 mg/l); BOD removal (from 211 mg/l to 7.0 mg/l); suspended solids removal (from 293 mg/l to 16 mg/l); turbidity reduction (from 145 NTU to 5.3 NTU); iron (from 5 mg/l to 0.3 mg/l); arsenic (from 500 μg/l to 10 μg/l); total coliform and fecal coliform removal (from 145×10^5 to 55 CFU/100 mL and 150×10^8 to 110 CFU/100 mL respectively), with desired pathogen levels as per WHO standards, i.e. $\leq 10^3$ CFU/100 mL. CSF reveals advantages such as low HRT (0.5–2.0 h), low energy requirement (0.04 kW h/m^3), no pre-treatment, high dissolved oxygen levels in the effluent, no biosludge production, no mechanical aeration and no odor, fish compatible water quality and evergreen ambience.

1. Introduction

Human activities in agriculture, mining, industry and commerce have led to considerable organic, inorganic and particulate loads on air, water and soil which have detrimental effects on the health of dependent population of land and water. Monitoring studies of water bodies reveal that the main source of pollution is the discharge of raw sewage [1]. Health risks rise sharply with the ingestion of unsafe water: diseases related to water sanitation are estimated to account for 4.0% of all deaths and 5.7% of the total disease burden occurring worldwide. Water scarcity has emerged as one of the most pressing problems in the 21st century. It is estimated that 2.7 billion people will face water scarcity by 2025 [2]. In India, it is predicted that one person in three will live in conditions of absolute water scarcity by 2025 [3]. In India surface and ground waters are diminishing and there is urgency to conserve fresh water resources. In India per capita yearly surface water availability in the years 1991 and 2001 was 2300 m^3 (6.3 m^3/d) and 1980 m^3 (5.7 m^3/d) respectively and these are projected to reduce to 1401 m^3 and 1191 m^3 by the years 2025 and 2050, respectively [4]. Total water requirement of the country in 2050 is estimated to be 1450 km^3 which is higher than the current availability of 1086 km^3. Alongside macro-water resource management, various micro-interventions such as rainwater harvesting and waste (grey) water reuse will have to be considered to meet the anticipated water deficit [5]. Technologies that treat wastewater and return good quality water into subsoil, rivers and oceans economically are need of the day. Wastewater of communities (sewage) comes with organic load but typically with low salinity levels. Purification of sewage for non-potable applications in gardening, construction, city cleaning, make-up water for industries, sports and recreation considerably mitigates problems of water shortage and reduces pressure on ground water withdrawal. Therefore, research into sewage treatment is needed in order to reduce the risks associated with improper sanitation, particularly in terms of wastewater reuse and for conserving the freshwater resources which being adopted by number of developing countries.

Conventional wastewater treatment includes physical, chemical and biological treatments viz. activated sludge process, trickling filter, lagoon, ozone oxidation, floatation, sedimentation, land treatment planted soil filter [6], date palm fibre media filter [7], subsurface water infiltration system (SWIS) [8] and wetland system. High capital cost and more importantly high operation cost limits their application, particularly in developing countries [9]. Interest in the natural technologies dates back to ancient practices and till recently it was the most acceptable method for wastewater treatment. Aquaculture and wetland concepts are relatively new developments for wastewater and sludge management [10]. Natural systems such as aquatic, aquaculture, wetland, and land treatments are now being offered. Several units of natural and constructed wetlands (CWs) for wastewater treatment are operational in Europe and North America [11–14]. CWs for wastewater treat-

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Table 1
Gross and simplified chemistry of reactions taking place in engineered natural system of CSF.

Respiration	
$(CH_2ON_xP_yS_zK_y)_n + nO_2 + nH_2O = nCO_2 + 2nH_2O$ + mineral (N, P, S, K) + energy (respiration)	(1a)
Anammox	
$1NH_4^+ + 1.32NO_2^- + 0.066HCO_3^- + 0.13H^+ \rightarrow 1.02\,N_2 + 0.26NO_3^- + 0.066CH_2O_{0.5}N_{0.13} + 2.03H_2O$	(1b)
Photosynthesis	
$nCO_2 + 2nH_2O$ + minerals (N, P, S, K) + sunlight = $[CH_2ON_xP_yS_zK_y]_n + nO_2 + nH_2O$	(2)
where x = 0.16–0.016; y = 0.01–0.001; z = 0.02–0.002; the lower value for terrestrial and higher value for aquatic productions.	
Nitrogen fixation	
$N_2 + 2H_2O$ + energy = $NH_3 + O_2$ (in soil)	(3)
$N_2 + 2H_2O$ + light = $NH_3 + O_2$ (in water)	(4)
Acidogenesis	
$4C_3H_7O_2NS + 8H_2O = 4CH_3COOH + 4CO_2 + 4NH_3 + 4H_2S + 8H^+ + 8e^-$	(5)
Methanogenesis	
$8H^+ + 8e^- + 3CH_3COOH + CO_2 = 4CH_4 + 3CO_2 + 2H_2O$	(6)
Adding Eqs. (5) and (6) give overall biomethanation chemistry	
$4C_3H_7O_2NS + 6H_2O = CH_3COOH + 6CO_2 + 4CH_4 + 4NH_3 + 4H_2S$	(7)
Mineral weathering	
$CO_2 + H_2O = HCO_3^- + H^+$	(8)
Primary mineral + $CO_2 + H_2O = M^{n+} + nHCO_3^-$ + soil/clay/sand	(9)
Nitrification	
$NH_3 + CO_2 + 1.5O_2$ = Nitrosomonas + $NO_2^- + H_2O + H^+$	(10)
$NO_2^- + CO_2 + 0.5O_2$ = Nitrobacter + NO_3^-	(11)
Denitrification	
$4NO_3^- + 2H_2O$ + energy = $2N_2 + 5O_2 + 4OH^-$	(12)

ment reveal constraints such as potential health hazards as possible epidemic outbreak, invasion of animal pests and bad odors [15,16]. Land treatment of wastewaters is known but is not used because (i) soil tends to choke due to sickness so large space requirement; (ii) uncertain water quality reaching the ground water.

As per carbon cycle, water supports 4 billion tons living carbon while soil and land support 800 billion tons live carbon. Life evolved in water 2 billion years ago but moved onto land impelled by thermodynamic logic that life longs for itself and evolution is about minimizing energy needs that it takes roughly 500 kJ/g live carbon per year to support life in water, 26 kJ/g live carbon per year in soil compared to 3 kJ/g live carbon per year on land. But conventional waste processing uses water as a medium contrary to the design of carbon cycle. So in CSF processing is carried out in soil. Accordingly, the central logic of CSF is to engage the fundamental process of nature.

Several technologies are available for disposal of organic pollutants. It is estimated that 60 billion tons of carbon (as dead organics) per year is produced globally every year; most of this is lost in litter respiration of nature. Only a small fraction of this energy is harnessed towards soil production and energy value of these organics is about 10 times the fossil energy consumed [17]. Most of the new

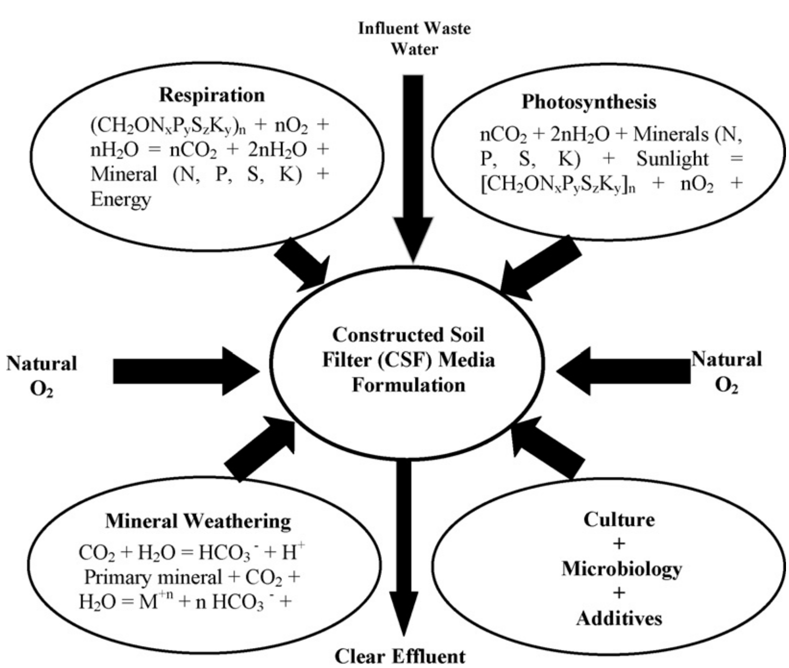

Fig. 1. Four elements of CSF media.

treatment technologies focus on the bioutilization or bioconversion of these organics. Diverting the energy of dead organics for soil production would open new opportunities and yield benefits to the health of soil and water; now being impaired by human activities.

In this context, we present constructed soil filter (CSF) system for wastewater renovation, and removal of iron and arsenic from water. The objective of the present study is to discuss the concept of CSF process, its ecological principle and novel approach to treat wastewater using CSF giving economics, comparison of conventional and non-conventional technologies and performance for water and wastewater treatment.

2. Constructed soil filter (CSF) system

2.1. Introduction

CSF is a process developed at Indian Institute of Technology-Bombay. CSF uses formulated media of completely or partially weathered rock environment wherein fundamental processes of nature viz. respiration, mineral weathering and photosynthesis brings about the bioconversion. In view of high oxygen levels, the CSF system finds promise in variety of application viz. water purification and sanitation also CSF shows oxidation of As(III) to As(V) and co-precipitation by iron salt removes arsenic below 10 μg/l WHO standard [18].

2.2. Principle

In CSF removal of organics occurs by adsorption followed by biological degradation (viz. conversion to CO_2). Oxygen is supplied by natural aeration. Acidity generated is regulated by chemical weathering of mineral additives. Photosynthetic activity of green cover serves as bioindicator for the kind of microhabitat in CSF. Rates of these fundamental processes are varying much more. Photosynthesis is slow because of availability of sunlight and low CO_2 levels; while weathering is slow because of surface area, moisture and low CO_2 levels. In CSF mineral weathering is enhanced significantly by adjusting particle size of minerals, moisture management and via high CO_2 availabilities being proximity to the source of CO_2 generation. Photosynthesis is slow and for waste conversion in CSF its role is to serve as bioindicator of abnormality. Accordingly, soil respiration and mineral weathering occur at desired rates and are regulated by adjusting organic loading rate, moisture and formulated mineral additives so as to achieve a designed level of bioconversion and hence water renovation.

Gross and simplified chemistry of CSF is given in Table 1. Respiration reaction (Eqs. (1a) and (1b)) brings about oxidation of the organics and inorganics wherein the iron and manganese serve as oxygen carrier, mineral weathering reaction (Eqs. (8) and (9)) regulates the pH of the environment while photosynthesis serves to bioindicate the health of the processing environment (Eq. (2)). In aerobic respiration oxygen demand is roughly equal to organic load. In CSF oxygen supply regulates the rate of respiration and 150–300 g/m^2 d of oxygen is typically observed; this value serves as the guideline for design. In view of this oxygen supply, process works essentially in the aerobic mode. Consequently respiration (Eqs. (1a) and (1b)), nitrogen fixation (Eqs. (3) and (4)), acidogenesis (Eq. (5)), nitrification (Eqs. (10) and (11)) are favored. In CSF due to high oxygen tension and redox potential, pathogens do not sustain. Anaerobic pathways of biomethanation (Eqs. (5) and (6)) and anoxic pathway of denitrification (Eq. (12)) are not preferred. However, nitrate losses do occur and this could be due to Anammox reaction (1b) and or denitrification reaction (12) of Table 1.

2.3. Application of CSF

The CSF system is applicable for water purification (primary processing prior to disinfection), wastewater purification and air purification. Typical applications include

(i) Rrainwater harvesting via storm water conservation.
(ii) Primary purification of drinking water.
(iii) Primary purification of swimming pool water.
(iv) Sewage treatment for reuse in construction, cleaning and gardening, make up water for swimming pools and industries, etc.
(v) Industrial wastewater treatment.
(vi) Removal of iron and arsenic from water.
(vii) Industrial air purification via scrubbing the air pollutant with water and then treating the scrubbed water through CSF.
(viii) New applications viz. retrofitting of conventional industrial wastewater treatment plants, biotower for space limiting situations, restoration of polluted water bodies, etc. are new aspects of future application.

3. Materials and methods

3.1. Elements of CSF

CSF consists of media of suitable mineral constitution, culture containing native microflora, geophagus worm *Pheretima elongata*, bioindicator plants. Indian and US patents cover the details [19]. Culture, media, plantation and additives, these are the four elements of CSF represented graphically in Fig. 1 and discussed below,

Underdrain	Stone rubble of a variety of sizes ranging up to gravel (2.0–200.0 mm), very coarse sand (1.0–2.0 mm), coarse sand (0.5–1.0 mm), medium sand (0.2–0.50 mm) and fine sand (0.1–0.25 mm).
Media	Formulated from completely weathered rock (soil) or partially weathered rock (preferably igneous Deccan Trap Basalt; PWDTB) as required and primary minerals of suitable particle size and composition.
Culture	Geophagus (soil living) worm *P. elongata* and bacterial culture from natural sources containing bacteria capable of processing cellulose, lignin, starch, protein, as well nitrifying and denitrifying organisms.
Additives	A rock dust of parent rock or formulated from natural materials (preferably igneous Deccan Trap Basalt) of suitable particle size and composition to provide sites for respiration and CO_2 capture and also regulates the pH.
Plantation	Green plants particularly with tap root system are employed which serves as bioindicator for the media environment. They also maintain root zone ecology in the media which helps in biodegradation.

3.2. Biological constitution

In CSF, process is regulated via vermiculture system. Vermiculture ecosystem is basically a consortium of different abiotic as well biotic elements selected after observation of their natural habitat and designated function to carry out specific activity in organic waste processing. According to Bhawalkar [20] various components of Vermiculture Ecosystem suitably chosen for organic waste processing and their respective functions are summarized in Table 2.

3.3. CSF process

The CSF process consists of the following: (a) Chemistry, Biology and Ecology in CSF facilitate all types of respiration (aerobic and anaerobic) depending on the nature and components of waste, load and oxygen availability; (b) suspended solids removed by filtration; (c) dissolved solids removed by filtration and bioconversion; (d) media, catalysts and additives provide sites for chemical and bio-

Table 2
Elements of vermiculture ecosystem (adapted from Bhawalkar [20]).

Elements	Ecological functions
Soil	Sink for organic carbon
Predator	Maintain prey population to match carrying capacity of the system
Bacteria	Work force for consuming organics
Fungi	Immobilize moderate levels of nitrate toxicity present in soils, plants or animals
Protozoa	Bioindicate water logged soil
Algae	Bioindicate waterlogged soil-containing nitrate exposed to sunlight
Anaerobic bacteria	Bioindicate overloading of organic carbon and organic nitrogen
Denitrifying bacteria	Bioindicate nitrate toxicity and bio remediate via denitrification
Nematodes	Graze on bacteria in water logged soil under acidic condition
Pests	Mobile pests such as insects get selected when there is surplus nutrition; stationary pests such as weeds get selected when there is deficient nutrition
Litter organism of soil	Soil organisms such as flies, cockroaches, ants, rats, red worms, mosquitoes, etc. indicate organic overloading of soil
Mosquito	Indicate accumulation of nitrate in aquatic bodies
Rock	Reserve of inorganics including nitrogen and therefore could be used for supplying minerals to a process and perhaps for locking excess nitrate as well

logical transformation [21]. The process consists of a bioreactor in a single or multistage systems and process design is arranged to achieve user needs. The schematic of the wastewater purification process is shown in Fig. 2 while Fig. 3 shows cross-sectional view of upper and lower media of CSF.

These systems are housed in RCC, stone-masonry or soil bunds or walls and consist of an impervious containment typically below ground, 0.7–2.4 m deep. It starts with a 0.3–0.7 m of underdrain layer of stone or rubble, above this a 0.4–1.7 m layer of media housing culture and bioindicator plants. Media is formulated using weathered material viz. either completely weathered soil or partially weathered rock (Deccan Trap Basalt) is used and found in and around Mumbai. Media consists of suitable mineral constitution, culture containing native microflora, geophagus worm *P. elongata*, bioindicator plants. In CSF system, geophagus worm—*P. elongata* (k selected organism) is engaged to maintain required soil microbial ecology. Physicochemical and microbial properties of one such media are given in Table 3.

3.4. Process description and operation

The process can be run as batch or continuous. In a batch process, wastewater is pumped and applied onto the top surface of the CSF system as shown in Fig. 2. The design has suitable provision for manual removal of suspended solids from the biofilter surface. Distribution of wastewater over the media is achieved via pumping, piping and distribution arrangements. Separate distribution lines are provided for raw wastewater as well as recycle water. Typical hydraulic loading is in the range of 0.036–0.25 m^3/m^2 h.

There are two modes of suspended solids handling. In one type, the arrangement of the media is in the form of alternate ridges and furrows. Ridges comprise of CSF media in trapezoidal shape and furrows are filled with additive layer and labeled as trench line (Fig. 3). In this type, a batch volume (V_L) of wastewater is pumped at rate (V_f) onto the trenches layer. Water first percolates through this trench line containing additive layer and gets collected into the collection tank. It was then pumped on to the media which in houses cultured soil media and distributed on it with the help of distribution system in order to achieve maximum solid liquid contact. The filtered water then gets collected into the collection tank and then recirculated (V_r) on to the media again for respective recycling time (Fig. 3). In another case, additive layer is provided at the top of the media directly and no trenches are provided. This is done to save the space and made available for dissolved organic solids processing. Water first passes through the additive layer and subsequently passes through the media. Filtration rates in the range of 0.05–0.1 m^3/m^2 h are maintained. Cross-sectional layout of layout of CSF plant at Worli, Mumbai for processing wastewater is given in Fig. 4. The process can be run as single stage or multistage depending on water quality desired. The recirculation mode is provided for further polishing of the effluent.

The suspended solids are trapped with additives. These materials are scraped manually and removed periodically. Dissolved organic and inorganic are oxidized and the water is purified further. The layout provides for manual removal of suspended solids

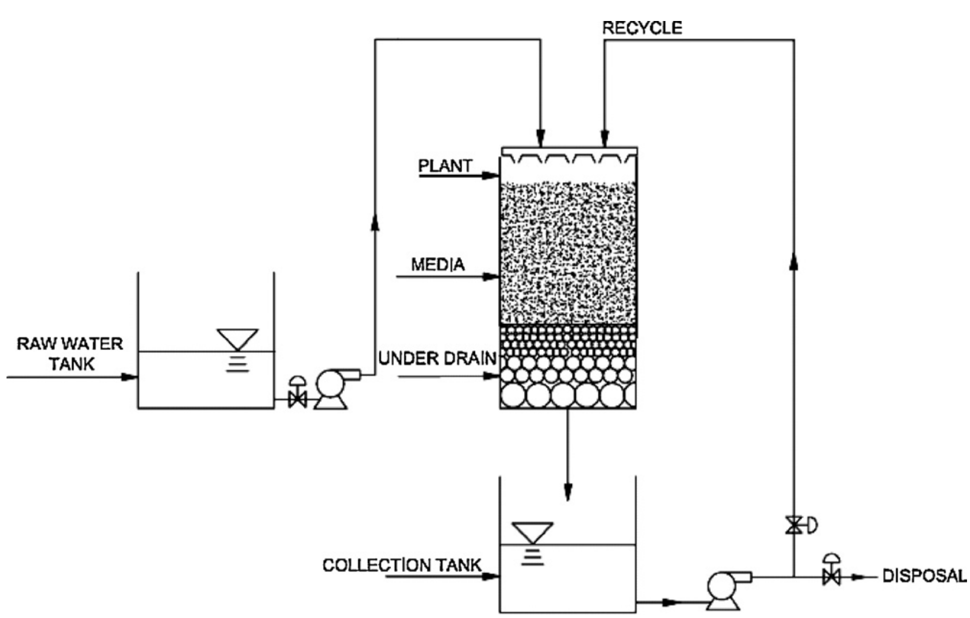

Fig. 2. Schematic of CSF process.

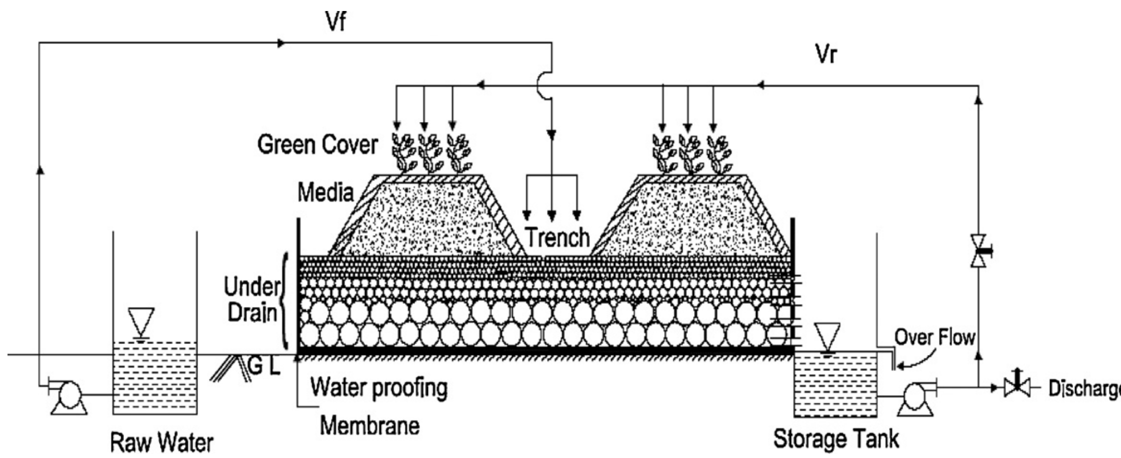

Fig. 3. Upper and lower media showing layout for processing water.

Table 3
Characteristics of media used in CSF.

Physicochemical properties	
Moisture content (%)	23.4 ± 5.1
Clay (g/kg)	11 ± 1.7
Silt (g/kg)	550 ± 25
Sand (g/kg)	400 ± 20
Gravel (g/kg)	38.0 ± 5.0
Soil texture (USDA scheme)	Sandy loam
Hydraulic conductivity (K_La; cm/s)	4.2×10^{-5}
pH soil suspension (1:5)	7.0 ± 0.20
Organic matter (g/kg)	1.3 ± 0.1
Total carbon (g/kg)	4.8 ± 0.4
Cation exchange capacity (m.e./100 g)	41.0 ± 5.8
Anion exchange capacity (m.e./100 g)	1.9 ± 0.4
Microbial properties	
Actinomycetes (CFU/g)	1.2×10^8
Heterotrophic plate count (CFU/g)	2.0×10^{12}
Protozoa	
Naked amoebae (cells/g)	8.3×10^6
Flagellates (cells/g)	8.3×10^4
Ciliates (cells/g)	8.3×10^4
Geophagus worm: *Pheretima elongata*	Present

from the biofilter surface as high quality fertilizer. Since oxygen levels are very high, respiration rates are high and so these fertilizer productions are very low.

Typically, a run consists of wetting cycle 8–12 h and drying cycle for 12–16 h. During the wetting cycle a clogging layer develops on the media due to the combined effects of algal growth, suspended solids deposition and bacterial growth in media. This clogging layer could impede water filtration such as reported for Soil Aquifer Treatment [22]. During drying cycle this clogging layer develops cracks due to respiration; so alternate wetting and drying are required for efficient performance. However in CSF system due to the work of soil organisms these problems are kept at bay and the need for such wetting and drying seems not essential if loading rates are within prescribed limits.

3.5. Analysis

Physicochemical and microbial analysis reported here is as per the standard methods for water and wastewater analysis [23]. pH and dissolved oxygen (DO) were measured using WTW (Germany) Inolab1 pH/Oxi meter. BOD and suspended solids were measured as per standard protocols. Samples were analyzed for various indicator and enteric pathogens by membrane filtration technique [23] using 0.45 μm membrane filters (PALL Life Sciences, Mumbai). Appropriately diluted (10^{-3}–10^{-7}) sample (100 mL in volume) volumes, in triplicate, was filtered and varied according to the group of organisms being enumerated and sample source (influent vs. effluent) to ensure 20–250 colonies in the Petri plate. Indicator organisms viz. fecal coliform (FC), total coliform (TC), fecal streptococci (FS), and coliphage were enumerated using specific media supplied from Hi Media Laboratory Pvt. Ltd., India. Plates were incubated for 24 h at 44.5 °C on M-FC medium for fecal coliform, 24 h at 37 °C on M-Endo agar for total coliform, and 48 h at 35 °C on M enterococcus agar for fecal streptococci. Physicochemical and microbial results are arithmetic means of 34 data sets in duplicates for site at Kanjurmarg, Mumbai [24].

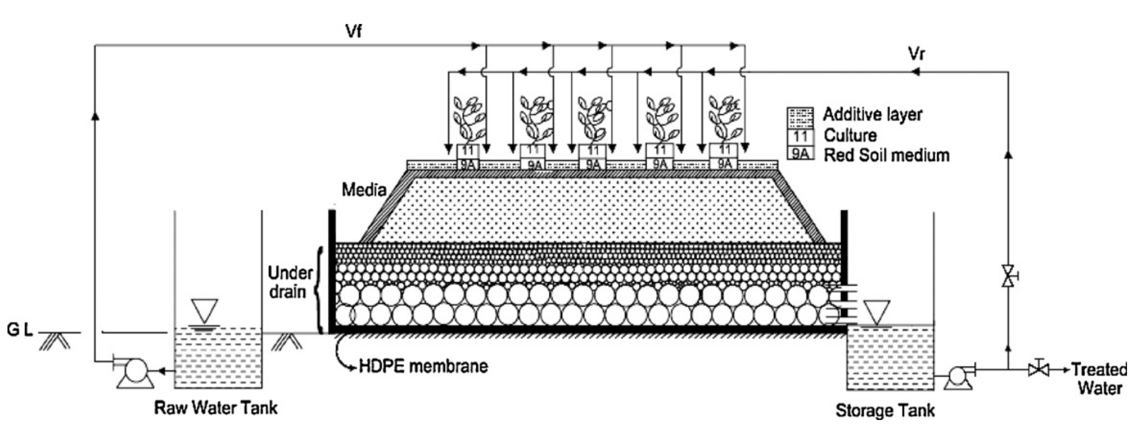

Fig. 4. Cross-sectional layout of CSF for processing wastewater.

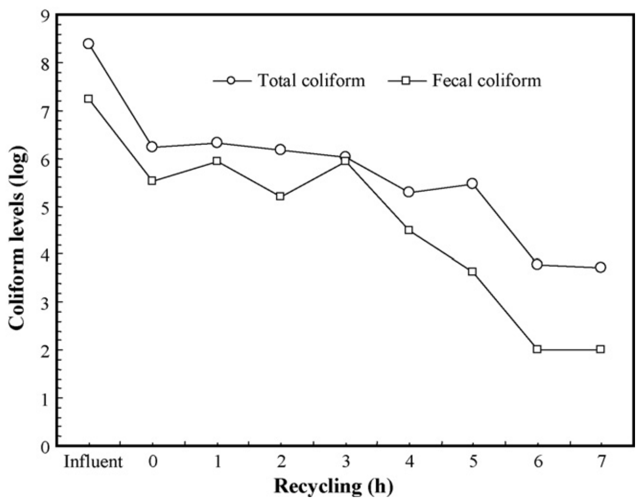

Fig. 5. Effect of extended recycling on indicator organism removal.

4. Results and discussion

4.1. CSF performance

The CSF plants show high COD, BOD, ammoniacal-N, nitrite-N, suspended solids, turbidity, and pathogen removal [25]. Earlier work on CSF indicates that for organic loading <0.15 kg/m^2 d, hydraulic loading <0.05 m^3/m^2 h and reduction potentials of >600 mV are typical in CSF [21]. And at these potentials (>600 mV) pathogens do not sustain while the predator prey interactions in the CSF environment bring about significant reduction in the pathogens. Also ammonia oxidation takes place effectively and removal rate constants of 5–10/h are common. Removal of suspended solids is very effective and very high rate constants are observed. Phosphates are found to get precipitated in the CSF environment. Since reduction potentials are large, nitrate removal by denitrification does not occur.

Fecal and total coliform level as per WHO guidelines for irrigation reuse, i.e. $\leq 10^3$ CFU/100 mL, was achieved with extended recycling of 6–7 h for SBT plant at Kanjurmarg located in Mumbai, India as shown in Fig. 5.

Fig. 6 shows the pictorial view of 3 MLD CSF plant at Worli, Mumbai. Table 4 summarizes the overall performance of the 3 MLD CSF sewage treatment plant for Municipal Corporation of Greater Mumbai (MCGM), Mumbai. Effluent pH (7.6) of all the plant was found to be near neutral. All effluent shows significant increase in dissolved oxygen levels (from 0.8 mg/l to 6.1 mg/l). Both BOD and COD show significant reduction from 350 mg/l to 20 mg/l and 211 mg/l to 7.0 mg/l respectively. Significant improvement in the clarity of water due to suspended solids removal (293 mg/l to 16 mg/l) from was observed [25]. Similarly, Zhang et al. [26] studied the Soil infiltration treatment (SIT) which gives 94.5% COD removal from wastewater.

Fig. 6. Pictorial view of 3 million litres per day (MLD) sewage purification CSF plant at MCGM, Mumbai, India.

Table 4
Performance of CSF plant at Worli, Mumbai, India.

Parameters	Influent	Effluent
pH	6.9	7.6 ± 0.2
DO (mg/l)	0.8	6.1 ± 0.3
Turbidity (NTU)	145	5.3 ± 0.2
COD (mg/l)	352	20 ± 0.5
BOD (mg/l)	211	7.0 ± 0.2
Ammonia (mg/l)	33.4	0.01 ± 0.02
Phosphate-P (mg/l)	0.47	BDL
Suspended solids (mg/l)	293.3	16 ± 3.0
Fecal coliform (CFU/100 mL)	145×10^5	55 ± 2.0
Total coliform (CFU/100 mL)	150×10^8	110 ± 3.0

BDL: below detectable level; CFU: colony forming unit (*Courtesy*: MCGM, Mumbai).

Overall CSF results show neutral to slight alkaline pH, saturation level dissolved oxygen concentration, drinking water level clarity of effluent, significant BOD and COD removal, almost complete removal of ammonia and phosphate, and bacterial removal of 6 log orders. With extended aeration at one of the site, coliform levels as per WHO standards for public recreation were obtained naturally without use of chlorine disinfection.

4.2. Arsenic and iron removal by CSF

Experiments carried out in laboratory based CSF system for arsenic and iron removal from water. It was found that there is a natural oxidation of As(III) to As(V) nearly complete conversion of As(III) to As(V) takes place and further arsenic removal by co-precipitation with ferric chloride. As As(III) is non-ionic in natural water pH 6.5–8; after passing through CSF, it get converted to As(V) by media which is ionic not get adsorbed on media as Table 5 shows correct mass balance of influent and effluent arsenic in water. CSF having very good potential for oxidation of As(III) to As(V) and then removal of arsenic from drinking water under all the treatment time conditions. The maximum removal of arsenic for both the filter media was achieved with a treatment time of 10 h and the residual value of arsenic was 0.008 mg/l by CSF. In all experiments the residual arsenic in water was found to be <10 μg/l in compliance with WHO drinking water standard. Table 5 shows that there is very little adsorption of As (V) in the bed. Almost 99% oxidation of As(III) to As(V) takes place using initial As(III) concentration of 300 μg/l.

Table 5 shows the results for removal of iron from water by CSF giving residual values of 0.056 mg/l in treated water. As CSF having its own ecology and oxygen reservoir as effluent dissolved oxygen in water samples are >5.0 mg/l as reported in previous study. The concentration of the dissolved oxygen in the liquid phase throughout the filter depth was always ranging from 5.0 mg/l to 5.25 mg/l which is sufficient to oxidize Fe(II) to Fe(III) forming $Fe(OH)_3$ which was detained on the support material of the filter. Influent pH was found to be 7.0 ± 0.2 and effluent was found to be close to neutral (7.4 ± 0.3) showing buffering capacity of CSF environment. The residual iron is <0.30 mg/l which is permissible limit for drinking water. Tekerlekopoulou et al. [27] observed iron (1–3 mg/l) removal from water in trickling filter and residual iron in the outlet was found <0.3 mg/l.

Table 5
Removal of arsenic and iron from water in laboratory CSF having an initial concentration of arsenic 300 μg/l and iron 5 mg/l with flow rate of 60 mL/min respectively.

Run time (h)	Oxidation of As(III) to As(V) CSF (μg/l)	$FeCl_3$ dose as Fe (mg/l)	Residual arsenic (μg/l) CSF	Residual iron (mg/l) CSF
2	294	35	12	0.128
4	295	35	10	0.089
6	296	35	8	0.077
8	296	35	8	0.067
10	296	35	8	0.056

5. CSF in comparison

5.1. With conventional technologies

Table 6 compares the performance of CSF with two conventional technologies viz. activated sludge process (ASP) and trickling filter (TF) for a typical 1 MLD sewage (with 250 mg/l COD, 150 mg/l BOD, 25 mg/l NO_3, 30 mg/l total N, 400 mg/l suspended solids and bacteria 10^7 CFU/mL).

Comparison shows that land requirement of CSF is comparable with ASP and TF. Performance with respect to COD, BOD, SS and Total N shows CSF more effective than the conventional one. Odor free, no mosquito breeding is the additional important feature of CSF in compare to wetlands. This is due to highly aerobic environment within CSF and no open channel of water during the operation process. Sludge management is the one of the most troublesome part in conventional units. In CSF only suspended solids trapped within additive layer is to be disposed off. In terms of energy requirement, CSF found to be more energy efficient (0.04 kW h/m^3) compare to conventional ASP and TF (0.2–0.34 kW h/m^3).

5.2. CSF in comparison with natural technologies

Natural technologies are of two types: aquatic and terrestrial but mostly based on aquatic systems viz. natural and constructed wetland, lagoon and various types of pond systems. Engineered soil treatment systems such as slow rate, rapid infiltration and Overland flow tend to exploit water and soil interphase and harnesses soil physical and chemical characteristics to improve performance. Wetland system like natural and wetland basically exploits aquatic-plant phase, rhizofiltration, etc. Nowadays many of these natural systems particularly wetlands are coupled with conventional units such as ASP as the secondary or tertiary treatment units. BOD is the limiting design factor for most of the natural technologies. Table 7 presents typical organic loadings for CSF in comparison to other natural treatment systems [28]. It reflects the superior organic handling capacity of CSF in comparison and is due to facilitated oxygen supply in the medium. Table 8 compares features of CSF and constructed wetland (CW) for a typical 1 MLD wastewater treatment with respect to space requirement, physicochemical and bacterial removal performance. Land requirement of CW is at least 35 times more than CSF, even though nowadays more area optimized designs are available for CW. HRT requirement of constructed wetland is very high due to biochemical constraints in aquatic phase and makes it more area intensive. In terms of performance comparison, physicochemical and microbial performances of both the system are comparable. According to Arcievala [29] land and power requirement of different processes are shown in Table 9, where CSF requires very less power near about 0.03 kW h/m^3 of water treated. Other technologies are energy intensive.

Constructed wetlands have been described as “mosquito-friendly habitats”. The attraction of large numbers of birds to constructed wetlands also increases the risk of transmission of mosquito-borne viral infections to humans in the vicinity of the wetland. The potential for conflict is typically highest in tropical regions. Many of the species found in constructed wetlands are known to be vectors of diseases of humans and animals. Most shallow aquatic ecosystems, including natural and constructed wetlands, provide suitable habitat for a variety of mosquito species. Mosquitoes have been reported in the literature as an issue of concern with the use of constructed wetland technology [30–32]. CSF in comparison do not show mosquito problem as there is no stag-

Table 6
CSF in comparison with conventional technologies for 1 MLD sewage processing unit.

Items	ASP	TF	CSF
Land, m^2	5000	5000	1135
COD[a], mg/l	80	80	<30
BOD[a], mg/l	25	25	<10
NO_3[a], mg/l	20	200	3–4
Total N[a], mg/l	20	20	3–4
SS[a], mg/l	100	100	10–20
Bacteria[a], CFU/mL	10^6	10^6	10^3–10^4
Odor	Yes	Yes	Not observed
Mosquito breeding	Yes	Yes	Not observed
Fish survival	Poor	Poor	No fatality
Sludge production, m^3/y	50	50	Not observed

[a] Outlet stream; typical sewage considered for above estimates: COD = 250 mg/l, BOD = 150 mg/l, NO_3 = 25 mg/l, total N = 30 mg/l, SS (suspended solids) = 400 mg/l, and bacteria 10^7 CFU/mL.

Table 7
Typical organic loading rates for natural treatment systems (adapted from Reed et al. [28]).

Process	Organic loading, kg/(ha d)
Oxidative pond	40–120
Facultative pond	22–67
Aerated, partial mix pond	50–200
Hyacinth ponds	20–50
Constructed wetlands	<120
Slow rate land treatment	50–500
Rapid infiltration land treatment	145–1000
Overland flow land treatment	40–110
Land application of municipal sludge	27–930
CSF[a]	2000–6800

[a] This study.

Table 8
CSF in comparison with natural technologies for 1 MLD sewage processing unit.

Description	CW	CSF
Land, m^2	40,000	1135
HRT, d	>7.0	0.1–0.2
COD[a], mg/l	30	30–48
BOD[a], mg/l	5–10	5–10
NO_3[a], mg/l	3–4	3–4
Total N[a], mg/l	3–4	3–4
SS[a], mg/l	10–20	<15
Turbidity; NTU	NA	<5 NTU
Bacteria[a], CFU/mL	10^3–10^4	10^3–10^4
Odor	Yes	Not observed
Mosquito breeding	Yes	Not observed
Fish survival	High	No fatality
Sludge production, m^3/y	Very small	Not observed

[a] Outlet stream; typical sewage considered for above estimates: COD = 250 mg/l, BOD = 150 mg/l, NO_3 = 25 mg/l, total N = 30 mg/l, SS (suspended solids) = 400 mg/l, and bacteria 10^7 CFU/mL.

Table 9
Land and power requirement of different processes (adapted from Arceivala [29]).

Process	Land required in warm climate (m^2/person[a])	Process power required (kW h/person-year)[a]
Conventional activated sludge	0.20–0.25[b]	12–15
Extended aeration	0.15–0.20	16–19
Trickling filters	0.20–0.30[b]	7–11
UASB + short detention pond	0.20–0.30[c]	Nil
Facultative aerated/lagoon	0.30–0.40[d]	12–15
UASB + 7-day pond	0.40–0.50	Nil
Oxidation pond	1.0–2.8[c]	Nil
UASB + duckweed + fish ponds	2.0–2.8[e]	Nil
Constructed wetlands (reed beds, root zone)	2.0–3.5[e]	Nil
Vermibased technologies	0.3–0.4	Nil
Constructed soil filter CSF (also called SBT)	0.3–0.4	Nil

[a] 'Person' signifies flow of 180 l/d and BOD of 50 g/d.
[b] Depends on type of sludge dewatering system (mechanical or open bed).
[c] Depends on pond location and detection time required to meet standards.
[d] Based on 3 m depth of water and ratio of embankment slopes 2 horizontal:1 vertical.
[e] Tentative, subject to more field work in India.

nant water. Oxygen transfer coefficients in constructed wetlands are typically 10^{-5}/s. In comparison CSF shows 10^{-3}/s typically.

Problems encountered with land treatment are: (i) groundwater or aquifer contamination, (ii) grazing animals exposed to pathogens, (iii) contamination of surface vegetation or offsite runoff, (iv) persistence of bacteria or viruses on plant surfaces and its potential threat to humans and animals, (v) increased risk of bacterial and viral transmission to groundwater aquifers due to coarse textured soils and high hydraulic loading rates, (vi) choking due to excess biomass commonly termed as "sewage sickness", and (vii) health hazard due to bioaerosol formation during sprinkling of wastewater onto the surfaces particularly during land treatment. With the impact sprinklers commonly used in the land application of wastewater, volume of aerosols produced amount to about 0.3% of water leaving the nozzle [32].

In CSF, these problems are addressed as below:

- Whole reactor is lined up with impermeable high density polyethylene (HDPE) membrane to avoid groundwater contamination if any and the whole water is collected in collection tanks.
- Complete area is enclosed with containment wall and the site is not easily accessible for animal grazing if any.
- In CSF, the role of plantation is assumed to be bioindicator and hence, there is no specific requirement of plantation except the one with tap root system is preferred. Edible vegetation and scented flowers are not selected purposely to avoid human contact and further nuisance.
- Use of sprinklers is avoided in CSF design keeping in mind the health risk associated with bioaerosols.
- In CSF, as a result of native protozoa and addition of geophagus worm *P. elongata*, excess biomass is not observed.
- Availability of space is the limiting factor in urban centres of the world. Hence area optimization is the need for of hour for natural processes. With inclusion of PWDTB as the medium, CSF area requirement is now reduced to 1135 m^2/MLD.

6. Economics

Sato et al. [33] have summarized economic evaluation of sewage treatment processes in India viz. activated sludge process (ASP), upflow anaerobic sludge blanket (UASB) reactor, and waste stabilization pond (WSP) in terms of capital cost, annual operation and maintenance (O and M) cost and land requirements. An attempt has been made to compare them with CSF. Their estimation shows the land requirements of 1.46 m^2/m^3/d, 2.0–5.1 m^2/m^3/d and 7–30 m^2/m^3/d respectively for a typical 72 MLD plant. Capital cost works out to be 54.5 US\$/m^3/d, 51–68 US\$/m^3/d, and 18–27 US\$/m^3/d respectively. Considering 35 years of life cycle cost, annual O and M cost is worked out to be 11.95 US\$/m^3/d, 2.0 US\$/m^3/d and 1.43 US\$/m^3/d respectively. In comparison, land requirement of CSF for a typical 100 MLD plant is estimated to be 1.1 m^2/m^3/d with capital cost of 93.8 US\$/m^3/d and annual O and M of 0.1–0. US\$/m^3/d. In conclusion, land requirement of CSF is 20–30 times less than WSP, 2–4 times less than UASB and comparable with ASP. CSF is found to be on slightly higher side in terms of capital cost but far cheaper in terms of annual O and M. Energy requirement of CSF is estimated to be 0.03–0.05 kW h/m^3.

7. Conclusion

CSF titled *Soil Biotechnology* works in a soil environment. It removes chemical contaminants as well as pathogen in a single evergreen facility open to atmosphere. With appropriate choice of retention time (or batch time) pathogen levels as desired can be achieved. Very low HRT (0.5–2.0 h), high hydraulic loading, no pretreatment, no chemical usage, absence of moving parts, high dissolved oxygen levels in the effluent, no biosludge generation, natural aeration, odor free, low energy requirement and green aesthetic environment are other unique features.

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