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Feasibility of a Novel (SHEFROL) Technology in Pre-Treating Eatery Wastewater at Pilot Scale

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Abstract: The wastewater ensuing from public eateries is higher in its chemical and biological oxygen demand (COD and BOD) as also its oil, grease, and protein content than sewage. For this reason such wastewater is much harder to treat; its content of fats, proteinaceous material, and xenobiotics mounting major challenges. But in most of the developing world about 80% of such wastewater is discharged untreated and the remaining is mixed with sewage going to the treatment plants. This happens due to the prohibitively high cost of treatment that is entailed if these wastewaters are to be treated by conventional activated sludge processes (ASPs) or a combination of anaerobic digestion and ASPs. The practice of allowing eatery wastewater to join sewage *en route* sewage treatment plants increases the load on the latter, especially due to the high fat and protein content of the former. The present work describes attempts to use the recently developed and patented SHEFROL® technology in affecting treatment of wastewater coming from a typical eatery. After establishing feasibility at bench scale, the process was tested in a case study at pilot plant scale for treating 12,000 litres/day (LPD) of wastewater being generated by the eateries situated in the campus of Pondicherry University, India. The capacity of the pilot plant was then expanded to 30,000 LPD. Despite operating the units at a very low hydraulic retention time (*HRT*) of 2 ± 0.5 h, due to the limitations of land availability, which translates to a rate about three times faster than a typical ASP, over 50% removal of COD and BOD, and similarly substantial removal of other pollutants was consistently achieved. Given that the SHEFROL units can be set up at a negligible cost, the findings indicate that SHEFROL technology can be used to significantly yet inexpensively pre-treat eatery wastewaters before either sending them for further treatment to conventional sewage treatment plants, higher-end SHEFROL units, or discharging them directly if neither of the other two options is available.

Keywords: eatery wastewater; sewage; SHEFROL; *Pistia stratiotes*; *Eichhornia crassipes*; *Alternanthera sessilis*; *Marselia quadrifolia*

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1. Introduction

1.1. The Complexity Associated with Eatery Wastewater Treatment

One of the most polluting and complex waste streams is the one which comes from eateries. Such a wastewater has high concentration of spices like chilly and clove, of fats, and of animal/vegetable proteins [1–3]. They also carry detergents used in the washing of hands and of the utensils [3]. All these constituents are slow to biodegrade—some don't biodegrade at all [4]—and interfere with several unit operations and unit processes of wastewater treatment systems which otherwise work well with sewage.

Attempts to address this problem have led numerous authors to explore ways and means by which physical, chemical, physico-chemical, biological, and hybrid methods can be applied for the treatment of eatery wastewater.

The physicochemical methods tried so far include sedimentation, coagulation, electrocoagulation, filtration, adsorption, and/or combinations of these [5,6]. The techniques explored include gravity and centrifugal separation, floatation, skimming and dissolved air flotation, coagulation-flotation, electro chemical break-up of oil-water emulsions, filtration with ultra-filters, biological filters, biological aerated filters, evaporation, and adsorption by powdered activated carbon, anthracite, other clay adsorbents, chitosan, bentonite, etc. [7–9].

The biological methods tried so far also cover a gamut: conventional activated sludge process (ASP), moving bed bioreactor (MBBR), rotating biological contactor (RBC), sequencing batch reactor (SBR), anaerobic baffled reactor (ABR), upflow anaerobic sludge blanket (UASB) reactor, anaerobic filter (AF) and several types of hybrids [10–12].

But all these physical, chemical, and physicochemical methods are besieged with problems of difficult-to-dispose chemical sludge, high energy requirements, and generally high operation cost, when dealing with eatery wastewater [13–15].

The drawbacks of biological methods are also formidable. Prime among them is the resistance of oily substances to biodegradation [16,17], and the presence of constituents like protein and phenols along with oily substances in eatery wastewater which interfere with the biodegradation process [18]. The requirement of large volumes of water per unit mass of oil separated is also a handicap [19,20]. Other limitations include leaching and flotation of biomass due to formation of lipid layer in secondary sedimentation tank, [21], volatilization of light hydrocarbons resulting in air pollution during aerobic biodegradation, and poor removal of oily and proteinous substances in anaerobic bioreactors [7,22–24]. Oily substances tend to envelop flocks of microflora, thereby seriously inhibiting the action of the microflora in all forms of bioreactors [25].

Conventional methods such as dewatering, gravity settling and incineration fare no better when it comes to handling eatery wastewater. Nor do membrane-based techniques [3,26].

Lakho et al. [27] set up a constructed wetland in a restaurant, to treat the combination of greywater and blackwater generated there. But it needed a train of other very expensive unit operations and processes downstream—involving activated carbon treatment, ultrafiltration, reverse osmosis, mixed bed ion exchange, remineralization, and ultraviolet disinfection—to complete the treatment. The operation and maintenance cost of such a system, as well as its ecological footprint, are likely to be prohibitive. Similar is the prospect of converting eatery wastewater into electrical energy in microbial fuel cells [28–30].

In developing countries like India, wastewater ensuing from most restaurants and hotels in India and their wash water is simply discharged untreated into public sewers which either lead to centralized sewage treatment plants or water-courses/open land. Given the fact that not more than 20% of the 1000 billion litres of greywater is treated in India [31,32]—the situation is similar in most other developing countries—it can be assumed that bulk of eatery wastewaters is discharged untreated in the developing world. Due to it, the high content of oil, grease, proteins, and xenobiotics present in the eatery wastewater either put extra burden on the sewage treatment plants, or get discharged untreated, thereby exacerbating the harm caused by untreated sewage [33–35].

In recent reports these authors have brought it out that the inability of the developing countries to treat most of its sewage stems not from an absence of technology but from the lack of the technology's affordability [36,37]. The conventional greywater treatment options based on activated sludge process and its variants (ASP & V) are prohibitively expensive to install, operate, and maintain. The alternatives based on constructed wetlands (CW) have low operational cost but require large land areas that are either unavailable or too expensive to be viable. Floating wetlands (FW) do not need land but are effective only in reducing the pollution of lakes/ponds, being too slow to handle the stronger greywater.

1.2. The Potential of SHEFROL®Technology

During attempts to develop a greywater treatment technology that is comparable in efficiency to ASP & V, yet inexpensive and eco-friendly, the present authors have invented a novel "sheet-flow-root-level" (SHEFROL) bioreactor. It is based on the use of short-statured plants which, upon reaching adulthood, are not more than 60 cm tall—for example *Alternanthera ficoidia*, *Plantago major*, and *Marsilea quadrifolia*. These plants are stocked to capacity in narrow and shallow channels while wastewater is made to flow through the channels as a 'sheet' thick enough to immerse only the roots of the plants. No soil or other container media is needed nor even any anchor or scaffold is required to support the plants. The reactor design and hydrology has been optimized to ensure maximum contact between the wastewater and the plant roots as also maximum plant-mediated and diffusive aeration of the passing wastewater. The combined gains are so strong that no auxiliary aeration is necessitated. As a result the SHEFROL-based greywater treatment systems need no machinery for stirring or aeration.

As discussed in detail earlier [36,37], wastewater treatment in SHEFROL® is primarily driven by the rhizosphere (root zone) of the vascular plants through which the wastewater is made to flow. The rhizosphere contains about 100 times more rich and diverse microflora than is present in other parts of the reactor. The action of the microflora towards degradation of organic carbon—as reflected in the reduction of BOD and COD—and in causing nitrification, is facilitated by factors such as oxygen transfer by the plants from atmosphere to the rhyzophere and by several biomolecules exuded by the roots. These include biopolymers which act as flocculants and cause removal of suspended solids. Nitrogen, phosphorous, and trace elements are removed partly by macrophyte uptake, and partly by other ways such as precipitation in the rhizosphere and chelate formation of metals with naturally occurring ligands. Numerous other biochemical, chemical, and physical actions, which are made to occur efficiently due to the design and operation of SHEFROL®, enable swift and effective treatment of wastewater in SHEFROL® systems [36,37].

On the basis of a series of studies [36,38–44], employing different species of macrophytes which, in their natural habitats, exist either as free floating weeds or marshy plants rooted in soil, or as terrestrial species, the efficacy of the SHEFROL® technology has been demonstrated. It has been seen that besides very efficient secondary treatment, which its main role, SHEFROL, also accomplishes significant levels of primary and tertiary treatment. And all these occur in a single pot, with no need to invest in any machinery, auxiliary energy or chemicals. Prior to the introduction of SHEFROL®, all plant-based wastewater treatment systems were confined to the use of aquatic macrophytes, but SHEFROL® design enables use of amphibious and terrestrial plants as well.

1.3. The Present Work

The largest and the most frequented eatery in Pondicherry University campus is its central canteen situated close to the author's laboratories. There is no system in place to treat the effluents of this canteen, nor of other eateries in the campus, and the waste is simply discharged into underground pipes which carry the effluent to pond-like depressions created for the purpose. It is a situation typical of Indian eateries and the eateries of most developing countries. The aim of the present work has been to explore the viability of SHEFROL® in the treatment of this 'difficult' waste stream in an affordable and efficient manner. Accordingly the present case-study was undertaken for pre-treating the wastewater generated by the eateries situated in the campus of Pondicherry University. The study is first of its kind in which such treatment of eatery wastewater has been accomplished to a significant extent by a technology which operates almost entirely on direct solar and gravitational energies, requiring no inputs of chemicals, auxiliary energy, or machinery. The technology is also green—literally as well as metaphorically—with no hazardous or otherwise problematic waste to dispose. Due to its high rate of treatment and its use of very inexpensive materials in construction and operation, the system has negligible cost.

2. Materials and Method

2.1. Lead-Up Studies

Before setting up pilot plants, lead up studies were performed on the bench scale SHEFROL® units and other contraption for these studies were manufactured using locally available and un-branded materials. Later the pilot plants were also set-up in the same manner as described later in this section. In order to trap food particles and oily substances, a four-tier filter unit was designed (Figure 1) and fabricated. Its top tier was made up of coarse mesh to hold vegetable pieces and similarly large particulates. The second tier aimed to remove rice and particles of similar size. Further down a strainer-type metal mesh was put to block-off tea powder and similar-sized particulate. The last tier had a cloth to separate still finer particles. A jute bag layer was kept directly below the cloth to soak oil.

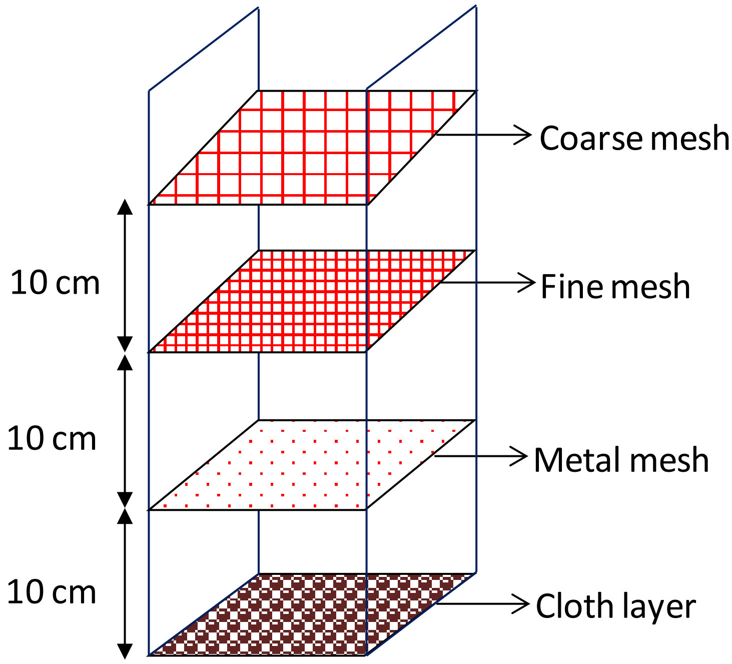

Figure 1. The four-tier filter unit used upstream bench-scale SHEFROL®-I system.

Bench−scale SHEFROL® channels (Figure 2) were fabricated and tried indoors (Figure 3) under simulated sunlight following the procedure standardized earlier [41,42]. After exploratory studies showed the systems to be working smoothly, a five-channel SHEFROL reactor was set outdoors. Four of its channels were used to explore the efficacy of different macrophytes of which two, *Eichhornia crassipes* and *Pistia stratiotes*, are free-floating aquatic weeds while the other two—*Marsilia quadrifolia* and *Alternanthera sessilis*—exist in nature as rooted in soil. The fifth channel served as control. A common equalization tank served all the channels, thereby ensuring that the characteristics of the wastewater entering all the channels were identical.

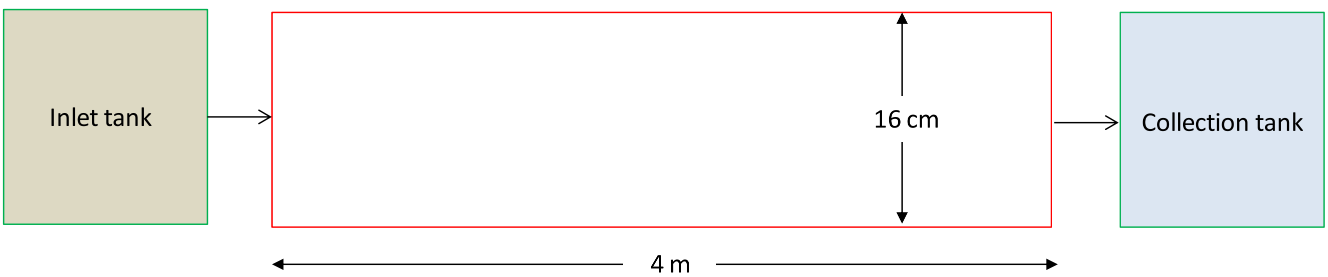

Figure 2. Dimensions of the channels used in the bench-scale SHEFROL®-I system.

Figure 3. Bench-scale SHEFROL®-I system.

In all cases the reactors were sized for targeted capacities, and hydraulic retention times (HRTs) in terms of litres per day; in other words litres per 24 h, on the basis of the expression:

$$HRT = \frac{V}{q} \quad (1)$$

where V is the reactor volume (litres) and q is the influent flow rate (L/h). The effective reactor (channel) volume was determined on the basis of the depth of the wastewater sheet, in turn by the length of the macrophyte roots. In practice, after V has been worked out, within certain limits q can be increased by reducing the HRT and can be reduced by decreasing the HRT. Accordingly the volume to be treated, in terms of L/day (LPD), can be varied within certain limits, for a given V.

2.2. Installation of the Pilot Plant SHEFROL®-II

After the success with the lead-up studies, a pilot scale SHERFOL®-II unit was installed near one of the manholes in the Pondicherry University campus which was attached to the pipe that carried the canteen wastewater from its source to the dumping site (artificial pond). As the space available for SHEFROL was limited, the system had to be sized to fit in that space while aiming to treat the average flow of 12,000 L per day (LPD) at the HRT of 5 h. The sizing was based on previous studies [45], which have indicated that an HRT of Ca 5 h provides the best trade-off between the rate of treatment and its extent to the SHEFROL® channels. The system dimensions were as in Figure 4.

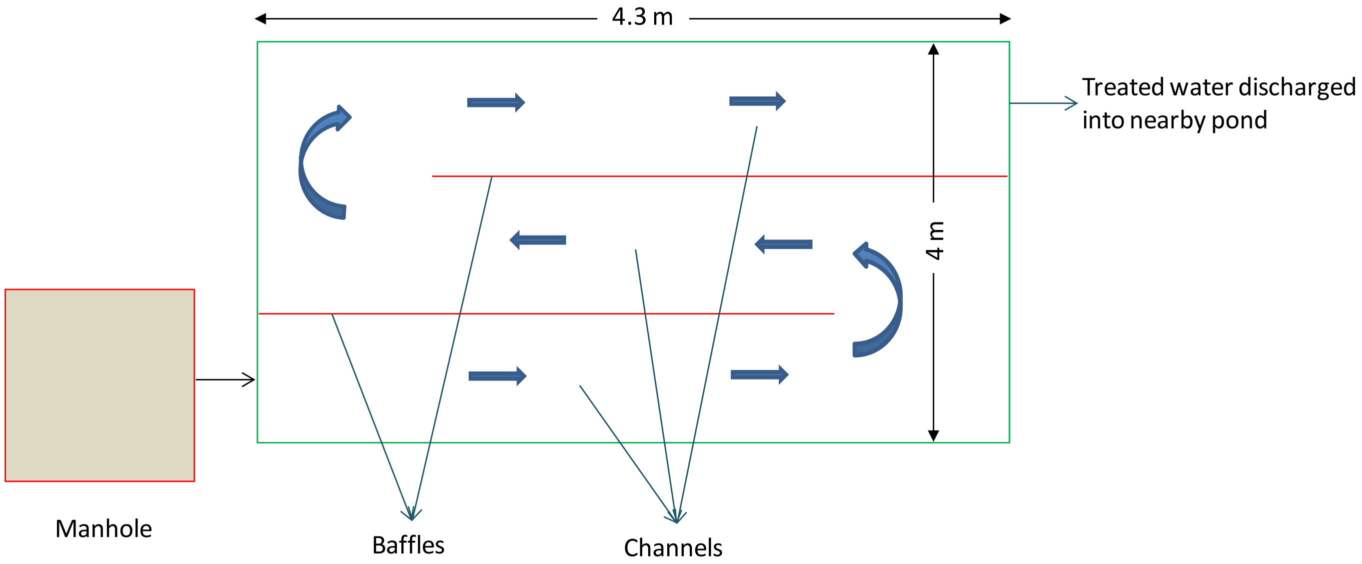

Figure 4. Schematic of 12000 LPD SHEFROL®-II.

2.3. *The SHEFROL®-III*

To overcome the problems of SHERFOL®-II, modifications were done to create SHERFOL®-III. Firstly the channel was made deeper to raise the head of the wastewater falling at the inlet point of the channel even as the liquid level in the trench was kept as before. The discharge pond earlier created by Pondicherry University was deepened and lined with LDPE sheets to prevent pollution of soil and groundwater by it. Secondly coarse and fine screens were put in the first part of the channel to remove particulates (Figure 5). Thirdly a baffle, made of a wooden plank, was placed at the end of the first leg of the channel to block-off oil. It had a clearing near the bottom to allow the oil-free water to pass (Figure 6). The cost of installation was ₹ 20,000/- (2020 value) as detailed in Table 1. However, after making these arrangements, when the system was put in operation, it because evident that oil-removal was still inadequate and better provisions to achieve oil removal were required. But even as the possible solutions were being worked out, the eateries were expanded and the wastewater flow increased two-and-a-half times to 30,000 LPD. As no space was available to increase the size of the SHEFROL® unit, the *HRT* had to be reduced two-and-a-half times, from 5 h to 2 h, to accommodate the increased inflow. For this reason the performance of SHEFROL®-III and SHEFROL®-IV has been assessed at the *HRT* of 2 h.

Table 1. Installation cost of SHEFROL®-III.

Material	Cost, Rs
Screens	2500
Mesh	1110
HDPE	1220
Pipe and valves	173
Adopter, super bond	5697
Digging by JCB machine	4350
Total	16,000/-

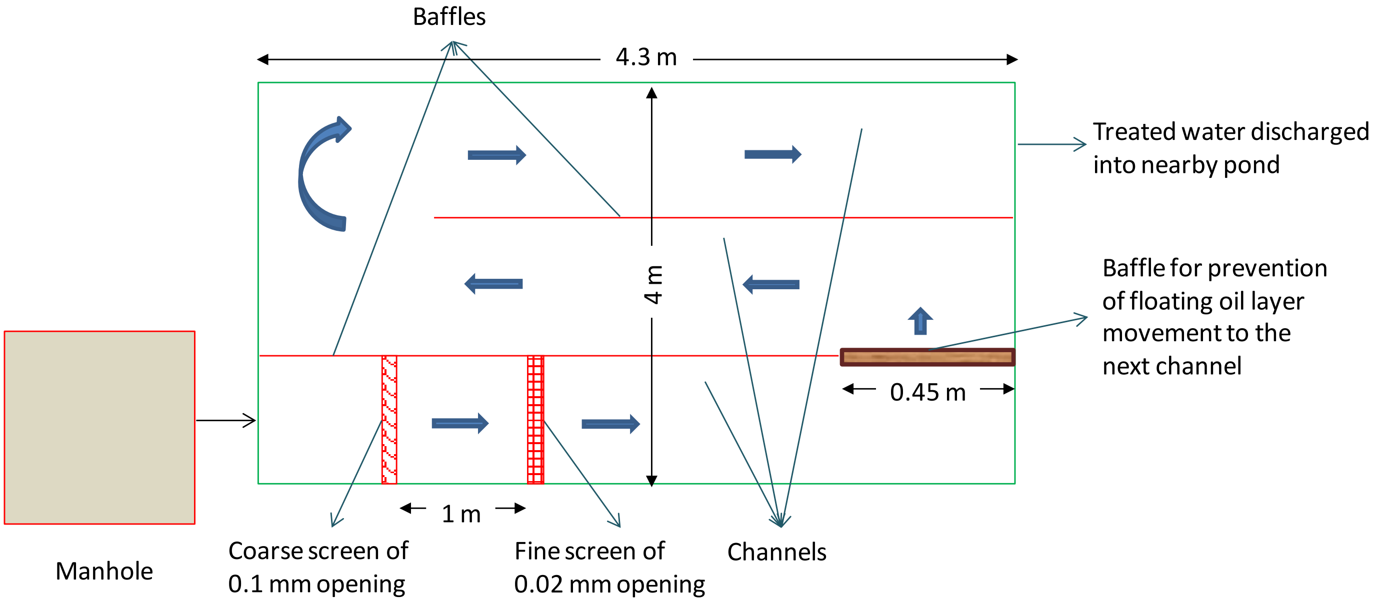

Figure 5. Screens and baffles deployed in SHEFROL®-III. Flat plan is given at left and isometric view at right.

Figure 6. SHEFROL®-III in operation.

2.4. The SHEFROL®-IV

To exercise better control over coarse solids and oily material, a rectangular strainer (Figure 7) was fixed below the mouth of the inlet pipe to black-off coarse solids. A cylindrical sedimentation tank of 1000 L was added upstream of the SHEFROL® channel (Figure 8). It was a sintex tank of which top was cut-off. Besides straining, the wastewater was passed through a jute bag to separate much of the oil. The whole unit was covered with nylon

(Figure 7) to prevent dried leaves from the nearby trees from falling into the system (which would have contributed COD as well as particulates).

Figure 7. The rectangular strainer used to block-off coarse solids in SHEFROL®-IV.

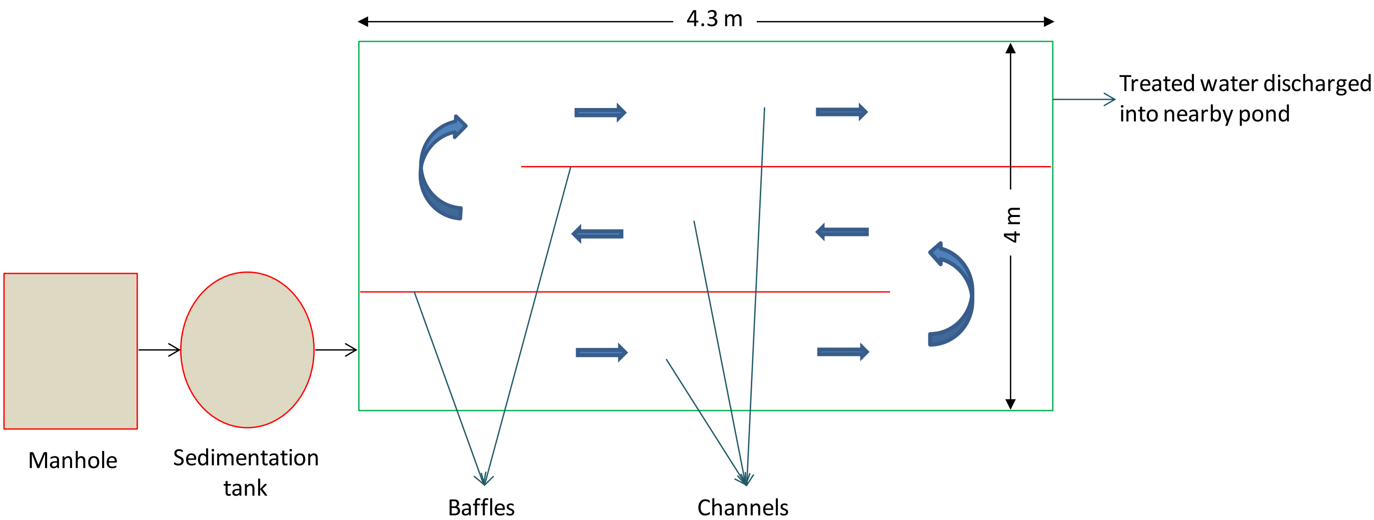

Figure 8. Schematic of SHEFROL®-IV.

2.5. Materials and Method

The samples to test the characteristics of the eatery wastewater and the extent of its treatment in SHEFROL were drawn from the points of the wastewater's entry to, and exit from, the SHEFROL® channels, respectively. The drawing of the samples, the preservation of its constituents for all the variables that were sought to be analyzed, and the analysis, were all done as per standard methods set by the consortium of American Public Health Association and American Water Works Association [46]. Three sets each of the influent and effluent samples were drawn daily at 10, 14, and 18 h, and separately pooled before they were analyzed at the earliest after the sampling. Of the targeted variables, BOD, SS, and TKN were determined by wet chemical methods and phosphorus was estimated spectrophotometrically with the help of a Lab India—UV 3000+ instrument acquired from Thane, India. The analysis of heavy metals was performed on a Perkin Elmer AA 800 atomic absorption spectrometer imported from USA, which was equipped with flameless atomizer accessory. Oil and grease were analyzed by the partition-gravimetric procedure [46]. The precision of the analysis was ensured on the basis of the reproducibility of each measurement. The accuracy was ascertained by determining recovery using the method of standard addition. Besides ensuring analytical quality control in general, the latter step also prevented matrix interferences from affecting the analysis results [47,48].

Whereas COD was monitored thrice a day at 10, 14, and 18 h, all other parameters were assessed once a week. The use of COD in this manner as an "indicator parameter" was done to ensure extensive and rapid process monitoring and control without incurring the prohibitive cost and effort associated with carrying out full analysis of all the samples. The four major reasons behind the identification of COD were (a) COD includes biological oxygen demand (BOD) and hence reflects the action of the macrophyte on most forms of organic carbon present in the wastewater; (b) it can be rapidly assessed in contrast to BOD which takes 5 days; (c) biodegradable carbon is the largest component that requires treatment in eatery wastewater; and (d) macrophytes always take up nitrogen, phosphorus, and other elements from water for their growth; hence, those components of the wastewater are certain to be reduced if the macrophytes can survive in the eatery wastewater and reduce its organic carbon. Earlier studies by the present authors have shown that the pattern of removal of COD with time approximates the pattern of removal of BOD, suspended solids (SS), total Kjeldahl nitrogen (TKN), soluble phosphorus (SP), and heavy metals from wastewaters of different characteristics and strengths in SHEFROL® channels planted with different species of macrophytes. These findings have validated the reasoning behind the use of COD as the indicator or "tracer" parameter [45,49,50].

3. Results and Discussion

3.1. The Lead-Up Studies

The characteristics of the canteen wastewater fluctuated widely across each day as well as day-to-day, as reflected in the variation in COD (Figure 9).

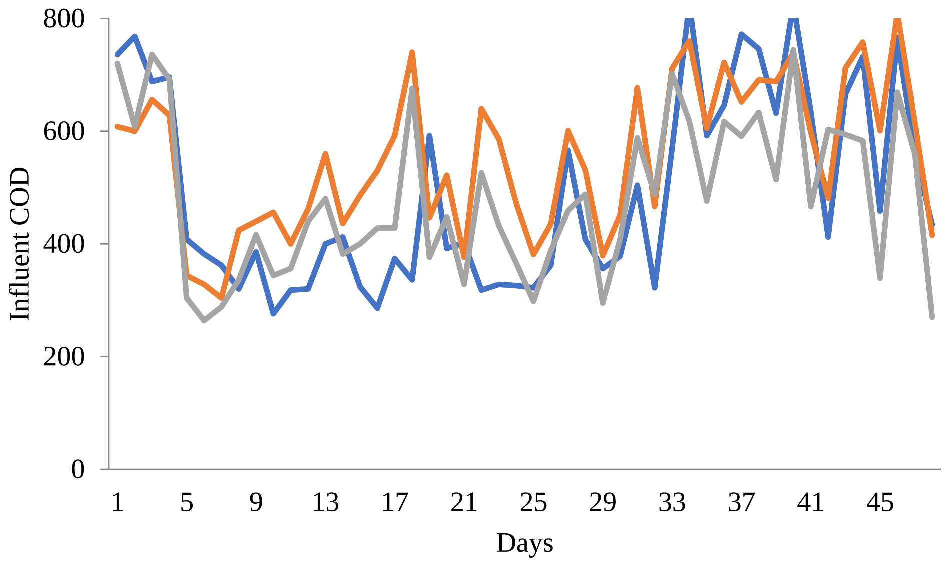

Figure 9. Variation in the influent COD. Red, grey and blue curves represent concentrations of influent COD at 10, 14, and 18 h, respectively.

The results of the performance of *E. crassipes* in terms of COD removal are presented in Figure 10. There was appreciable treatment from the very first day which reached steady state in about nine days and then hovered in the 75 ± 5% range. Despite strong fluctuations in the influent COD at different times of the day, and at different days, the level of treatment remained remarkably steady.

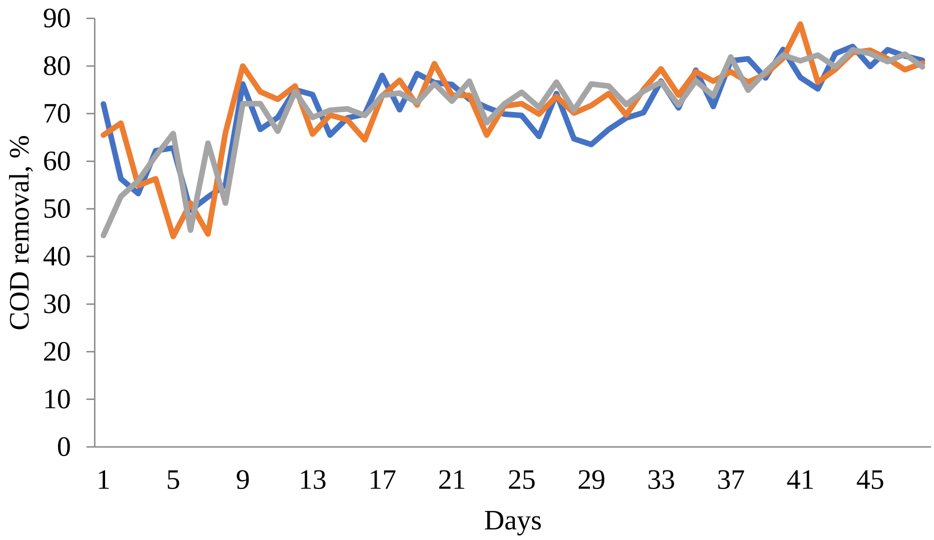

Figure 10. Removal of COD in the channel planted with *E. crassipes*, in SHEFROL®-I. Red, gray and blue curves represent COD removal occurring at 10, 14, and 18h, respectively.

As discussed briefly in Section 1.2, a large number of biological, biochemical, chemical, physical, and physico-chemical factors operate to cause the levels of contaminant removal that are observed in SHEFROL®. The effectiveness of these factors is maximized by the special way in which SHEFROL has been designed and is made to operate. The distinguishing features include:

(i). Maximization of the contact between wastewater and macrophyte roots. As the roots are the hub of most of the activities that lead to contaminant removal, this contributes greatly to the reactor efficiency

(ii). Favourable reactor hydrology. Kadlec and Wallace [51], Vymzal [52], Ilyas and Masih [53] and others have noted that a reactor hydrology that promotes aeration in macrophyte-based wastewater treatment systems also contributes to better removal of COD, BOD and nitrogen. The SHEFROL® hydrology is such that it not only maximizes treatment efficiency by maximizing the wastewater-rhizosphere contact, but also facilitates atmospheric aeration. Sheet-flow causes maintenance of shallow wastewater depth, enabling easy atmospheric aeration. The aeration is aided by the agitation caused as the wastewater moves through the macrophyte roots. These factors, and the transport of oxygen by the macrophytes from their leaves to the roots via their stem, ensure that no anoxic conditions develop and the wastewater is well-oxygenated. This overcomes the problem of oxygen deficit faced by all constructed wetland systems, and which is their major drawback [36,53].

(iii). Flexibility in the choice of the main bioagents (the macrophytes). Not only free-floating aquatic plants, and the marsh plants like *Marselia quadrifolia* [41] which are anchored by their roots in nature, SHEFROL® can accommodate even terrestrials like *Alternanthera ficoidea*, [39], *Achyranthos aspera* [40] and *Catharanthus roseus* [50]. This flexibility enables addition in SHEFROL® channels of plants which show special ability in removing certain targeted constituents. Such plants have not been, and can not be, deployed in other types of macrophyte-based wastewater treatment systems.

Due to the combined effect of these features, wastewater treatment occurs much more rapidly and effectively in SHEFROL® than it does in the pre-existing systems. They also contribute to the versatility as well as inexpensiveness of the SHEFROL® systems. Other notable features of SHEFROL® design and operation are:

(a). No matrix/scaffold of any kind, nor any gravel/sand/stone bedding is needed to anchor the plants in SHEFROL, unlike in other (reported) hydroponic/thin film wastewater treatment systems [54]. This obviates the need to invest in such support systems, reduces carbon footprints, makes the system more easy and quicker to set up and operate, and ensures that the use of the available reactor space is maximized.

(b). In contrast to other plant-based systems reported so far, SHEFROL® units require. no auxiliary aeration device, nor does it need any external mixing/agitation, etc.

(c). SHEFROL® units are found to be several times faster than the other plant-based systems employed thus far and are comparable in efficiency with much more expensive conventional systems based on activated sludge process/fluidized bed/sequential batch technologies.

(d). The configuration of SHEFROL® and its components ensure optimal and flexible space utilization besides ease of capacity enhancement.

(e). SHEFROL runs exclusively on gravitational and direct solar energy. Due to this, the operation and maintenance requirements are so simple that even laypeople without formal education can manage these units after minimal training.

All of the factors enumerated above appear to have contributed to the inexpensive installation and modification of the various versions tried by the authors, and the substantial contaminant removal that has been observed. However, at the present state of the knowledge in this field, it is not possible to quantify the extent of contribution of different factors in removing different contaminants. For the same reason no analytical models exist to describe and forecast the performance of SHEFROL or any other macrophyte-based wastewater treatment system.

The performance of the other three species was comparable, as summarized in Table 2. *P. stratiotes* had about 10% lesser, though still substantial, effectiveness in COD removal than *E. crassipes* and at steady state it achieved about 65 ± 5% of COD removal. It was quite effective in phosphorous removal as well, even if less so than *E. crassipes. M. quadrifolia* and *A. sessilis* were also very effective in the treatment of the settled canteen wastewater. In all cases the reactor output was steady and consistent despite wide fluctuations in the quality of the inflows.

Table 2. Relatives performance of the four species of macrophytes used in SHEFROL®-I.

Characteristic	Influent Concentration Range, mg/L	Range of Treatment, %, Achieved at Steady State with			
		E. crassipes	*P. stratiotes*	*M. quadrifolia*	*A. sessilis*
COD	264–826	70–84	58–71	58–71	60–67
BOD	108–330	70–78	59–70	66–70	54–59
SS	310–690	83–89	79–86	85–93	81–87
TKN	53–77	51–62	49–58	58–69	53–58
P	5–11	68–71	63–69	58–62	51–54
Cu	2–6	40–44	38–41	46–49	42–46
Ni	1–4	31–35	30–36	33–37	30–4
Zn	3–8	43–46	44–50	47–51	48–54
Mn	2–4	29–34	28–33	30–36	31–34

Pest attacks. On one occasion some of the *M. quadrifolia* leaves were seen folded. When such leaves were unfolded, caterpillars were found inside; feeding upon the leaves. The infected leaves were trimmed off and cow urine was applied. It totally repelled the pest attack. On another occasion pistia roots got infected with rat−tailed maggots. In this case, too, application of cow urine led to swift repulsion of the pest.

3.2. The Performance of the SHEFROL-II

When the wastewater was initially let into SHEFROL®-II it was hoped that during its earlier passage through the underground pipe it might have shed most of its coarse solids. But it was not so, and all kinds of very coarse solids came with the stream into the SHEFROL®-II. Oil and grease came, too. The combined burden of these inputs was too much for the plants in the channels to handle. Even the most sturdy and resilient of the four species tried—*E. crassipes*—could not cope up with the onslaught of coarse solids, oil and grease, and quickly withered. The extreme variation in the rate of inflow, which abruptly changed by thousands of litres per hour (Table 3), also added to the burden.

Table 3. Pattern of eatery wastewater flows into SHEFROL®-II.

Day	Flow Rate L/h								
	10 h	11 h	12 h	13 h	14 h	15 h	16 h	17 h	18 h
Monday	1324	2750	102	314	1846	52	54	4180	517
Tuesday	981	3200	134	297	2120	78	73	3620	724
Wednesday	1156	2908	98	381	1992	89	62	4705	818
Thursday	830	3126	127	423	1601	64	87	3950	637
Friday	1650	3050	171	400	2000	83	69	4684	884
Saturday	94	23	11	57	112	4188	-	-	-

3.3. *The Performance of the SHEFROL-III*

The results of monitoring of the inlet and the outlet water quality, which reflect the performance of SHERFOL®-III in treating canteen wastewater when *E. crassipes* is used as the main bioagent, are summarized in Table 4. Given the extremely low capital cost of the unit, its practically nil maintenance cost, and the complexity of the influent, >50% removal of COD and BOD (for most part) and nearly as much removal of other pollutants was occurring, which can be considered significant. Another spell of continuous monitoring gave similar results; indeed showing minor improvements. Based on the operational experience with other SHERFOL® installations [45] it can be said that if a polishing pond is added downstream of these SHERFOL® channels, planted with *M. quadrifolia* or *A. sessilis*, it can take the overall pollutant removal efficiency beyond 85%.

Table 4. Treatment of canteen wastewater achieved in SHEFROL-III, planted with *E. crassipes*, at an *HRT* of 2 h.

Characteristic, mg/L	Range at the SHEFROL Inlet, at 11 h. mg/L	Treatment Achieved, %	Range at the SHEFROL Inlet, at 14:30 h, mg/L	Treatment Achieved, %	Range at the SHEFROL Inlet, at 17:30 h, mg/L	Treatment Achieved, %
COD	630–780	50–57	520–611	49–54	429–772	48–55
BOD	380–435	69–74	210–395	70–75	170–330	69–74
SS	270–305	52–55	210–256	51–56	165–311	52–56
TKN	39–51	55–61	41–59	57–62	29–36	59–66
P	6–11	59–64	8–12	61–65	7–13	6–64
Cu	3–6	41–45	4–7	40–44	2–5	39–43
Ni	2–4	31–35	1–4	30–36	2–5	31–35
Zn	4–7	42–45	5–9	40–44	3–6	41–45
Mn	2–4	29–33	1–3	30–35	0–4	30–34

The experience with SHERFOL®-III was suggestive of the need of better arrangement to remove oil and subsequent effort was focused on it.

3.4. *Performance of SHEFROL-IV*

The results of a long spell of continuous monitoring of the performance of SHEFROL®-IV are summarized in Table 5. Despite handling much stronger wastewater—of COD reaching upto 4800 mg/L—the system kept its performance level as robust and steady as witnessed with other SHEFROLs®—before and since. The pattern in which concentrations of variables fluctuated in the influent was mimicked by the variables in the effluent as well. It was typical of the performance of all the SHEFROL® variants.

Table 5. Treatment of canteen wastewater achieved in SHEFROL-IV, planted with *E. crassipes*, at an *HRT* of 2h.

Characteristic, mg/L	Range at the SHEFROL Inlet, at 11h. mg/L	Treatment Achieved, %	Range at the SHEFROL Inlet, at 14:30 h, mg/L	Treatment Achieved, %	Range at the SHEFROL Inlet, at 17:30 h, mg/L	Treatment Achieved, %
COD	895–4890	55–62	780–4944	57–64	880–4992	54–66
BOD	295–645	70–75	315–688	69–75	360–911	66–74
SS	350–1690	59–67	322–1780	57–66	335–1822	60–67
TKN	51–66	56–63	48–71	55–62	51–58	59–65
P	29–62	58–63	33–63	60–66	41–73	66–71
Cu	2–5	40–44	2–4	37–42	3–6	39–45
Ni	1–3	29–31	2–3	31–33	0–2	30–35
Zn	4–7	39–45	3–6	40–44	3–5	37–42
Mn	2–3	27–30	0–3	26–29	1–2	27–31

As per the Indian standards for discharge of wastewater on land or in public sewers [31], concentrations of Cu, Zn, Ni and Mn in the wastewater should be less than or equal to 3, 5, 3, and 2 mg/L, respectively. These values were achieved at most times (Tables 3–5). Moreover, this SHEFROL® system aims not to fully treat the eatery wastewater but to quickly but significantly and inexpensively pre-treat it so that if it is going into sewage treatment plants, those plants do not get overloaded/overwhelmed. And if it is being discharged untreated, the harm such disposal causes can be substantially reduced.

3.5. Attempts to Biodegrade the Oily Components and Exploration of Freely Available or Inexpensive Martials as Possible Oil-Absorbents

In the work reported elsewhere [55] extensive microbiological studies were done to identify the fungi present in the wastewater which might be utilizable to degrade the oily components. It was seen that *A. niger* had significant consumption of cooking oil. In the same study dried forms of nine materials, which included four weeds *E. crasspies*, salvinia (*Salvinia molesta*), milk weed (*Asclepius cordifolia*), and grassy weed (*Imperata cyclindrica*); banana trunk fiber, rice husk, rice stalk, kenaf, coir pith, and jute bags—were explored as possible oil-absorbents. *S. molesta* was seen to be most efficient in oil removal, followed by *E. crasspies* and kenaf.

4. Directions for Future Work

Given that both *S. molesta* and *E. crasspies* are freely and widely available weeds, these findings indicate that further work should be focused on designing effective and inexpensive oil removing systems based on these weeds, to be used in tandem with SHEFROL® units. It is expected that an oil removal system upstream SHEFROL®, and a 'publishing pond' downstream SHEFROL® may take the wastewater COD removal rates to 85% and beyond. As detailed elsewhere [45], the 'polishing ponds' are nothing but mini-SHEFROL units of short hydraulic retention times in which macrophytes of species different from the ones used in the min SHEFROL® are deployed. They add 10–15% to the cost of the main SHEFROL®, which still adds up to an overall cost several times lesser than the next cheapest treatment system of comparable efficiency.

5. Summary and Conclusions

A novel phytoremediation technology based on recently developed, patented, and trademarked sheet-flow-root-level (SHEFROL®) bioreactor has been successfully applied in the pre-treatment of eatery wastewaters at pilot scale. The study was taken up in view of the facts that (a) eatery wastewater represents a highly polluting and difficult-to-treat waste stream; (b) in developing countries about 80% of it is discharged untreated while the remaining is mixed with sewage going into the sewage treatment plants, adversely effecting their performance; and (c) the technologies available for treating eatery wastewater are too expensive to be affordable by most developing countries. It led to the development of a process with which substantial pre-treatment—to the extent of removing half of its pollution load—of eatery wastewater can be accomplished at negligible cost.

After establishing feasibility at bench scale, the process was tested at pilot scale for treating 12,000 L/day (LPD) of eatery wastewater. The capacity was then expanded to 30,000 LPD. Despite operating the units at a very low hydraulic retention time (*HRT*) of 2 ± 0.5 h, due to the limitations of land availability, which translates to a rate about three times faster than a typical ASP, over 50% removal of COD and BOD, and similarly substantial removal of other pollutants was consistently achieved. Considering that SHEFROL units can be set up at a negligible cost, the findings indicate that SHEFROL technology can be used to significantly yet inexpensively pre-treat eatery wastewaters before either sending them for further treatment to conventional sewage treatment plants, SHEFROL-based polishing units, or discharging them directly if neither of the other two options is available.

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