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Treatment of rural wastewater by infiltration percolation process using sand-clay fortified by pebbles

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ABSTRACT

The quest for simple, low-cost and high-performance decentralized wastewater treatment system for rural application in developing nation necessitated this study. The ability of sand-clays fortified by pebbles in rural wastewater treatment was investigated in this article. Clay samples, collected from northeastern Tunisia, were characterized by studying the mineralogical and geochemical composition using X-ray diffractometer and atomic absorption spectrophotometer, respectively. Permeability studies were conducted to determine the best combination ratio (3:1) of sand-clay/pebbles. The sand-clay mixture, containing 90% of sand and 10% of clay by weight and fortified with pebbles in a ratio of 3:1, this reconstituted sand filter, gave the optimum wastewater purification and appropriate permeability, the values are 2.18×10^{-6} m/s for no fortified sand-clay and 2.29×10^{-5} m/s for fortified sand-clay in ratio 3:1. The performance efficiency of the fortified column was studied and the results showed a decrease of nitrogen (65%), biochemical oxygen demand (75%), chemical oxygen demand (73%), and bacteria such as fecal coliform (0.7 Ulog), fecal streptococci (4 Ulog), and total bacteria (2 Ulog).

Keywords: Wastewater treatment; Infiltration percolation; Fortified sand-clay; Pebbles; Rural effluent; Column

1. Introduction

The treatment of wastewater is a compulsory requirement for sanitation and is being subjected to increased rigor [1]. Among the wastewater treatment processes recommended are those which belong to the attached growth family: infiltration percolation [2], planted reed filters with vertical or horizontal flow [3], buried filters [4], underground spreading, [5] and surface spreading [6]. Three of these modes of treatment use sand as a filter material and as a biomass support: (1) infiltration-percolation beds, (2) buried filters, and (3) planted reed filters. They are regarded as being particularly suitable for the rural environment, due to their simplicity of operation and maintenance. The qualities of discharge that can be obtained represent benefits to small communities.

Studies on systems treating more concentrated effluents [7], particularly in the field of small agro-food wastewater treatment plants [8], have also identified potential limitations to attached growth systems such as the accumulation of residual matter produced by the degradation of organic matter in the filtration beds.

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Biological contactors, oxidation ponds, etc. were developed by the middle of twentieth century [9]. The rudiments of the design of some of these treatment methods were based on simple scientific principles, but their construction and operation are associated with intensive energy requirements and highly skilled operators who are familiar with the operation and maintenance of such systems.

Clay is composed of particles smaller than 2 μ, which places them within the limit of the colloidal state [10]. Owing to their physicochemical properties (lamellar structure, high surface area, and large cation exchange capacity (CEC)), clay minerals have great potential to remove heavy metals and organic compounds [11]. Phyllosilicates and zeolites are known to adsorb and exchange many cations and hence restrict their mobility and bio-availability [12]. Studies have shown that clays have high potential in water treatment, but their low permeability has continued to restrict their use as a filter medium [13]. Bailey et al. [14] suggested the use of artificial support for use in columns containing clay to improve the low permeability. It is on this premise that the potential of sand-clays fortified with stone-pebbles in rural wastewater treatment are being studied. Amongst the materials that have been introduced as percolator in on-site treatment systems are soil materials such as sand [15], loam [16], and peat [17]. A number of researchers have reported the use of clays and other silicate materials for the treatment of both domestic and industrial wastewater. The use of sepiolite columns has been reported by Brigatti et al. [18] for the treatment of heavy metal-contaminated water. Viraraghavan and Kapoor [19], Sharma et al. [20], and Cadena et al. [21] have also used clays in different forms to treat wastewater.

The choice of the sand constituting the infiltration bed is one of the key elements and is the main subject of this article. It must have a sufficient initial permeability in order to ensure an adapted infiltration speed after colonization by the purifying biomass. The physicochemical properties of clays are responsible for their high adsorptive power and CEC, which can be harnessed for rural wastewater treatment. The aim of this study was to design a reliable, technologically simple, and low-energy-consuming decentralized wastewater treatment system using sand-clay fortified with stone-pebbles to enhance the permeability to wastewater.

2. Materials and methods

2.1. The percolator filter

Sand and pebble samples were collected from Borj Hefaidh region in the northeast of Tunisia. It was washed and sifted to a grain size of less than approximately 1 mm. Clay materials were collected from the region of Grombalia. The processing of the clay sample collected from the Grombalia preparation included air-drying crushing by mortar and pestle, and passing through a 60-mesh sieve.

Sand-clay, mixed in the ratio of 9:1 was mixed with stone pebbles in the ratio of 3:1 based on the results from permeability studies [22]. Pebbles play an important role in improving permeability. Twenty-seven kilograms of sand were mixed with 3 kg of clay, 10 kg of stone pebble were added in the same recipient, and all of the mixture was transferred to a 20-cm-diameter column of Plexiglas. A 10-cm-deep layer of gravel having an average diameter of approximately 2 cm was at the base of the column. The column was covered by aluminum paper to protect it from light and was flushed several times with distilled water to wash off all organic debris present in the sand-clay. The influent loading started 24 h after the flushing of the fortified sand-clay column with distilled water. The hydraulic loading rate was 100 L/m^2 d. The used column is shown in Fig. 1. In order to assess the treatment potential of the fortified sand-clay column, 20 L, in one load, of the wastewater sample were made to pass through by pumping with a peristaltic pump. The treated effluent was collected by gravity flow and analyzed for physicochemical and bacteriological characteristics.

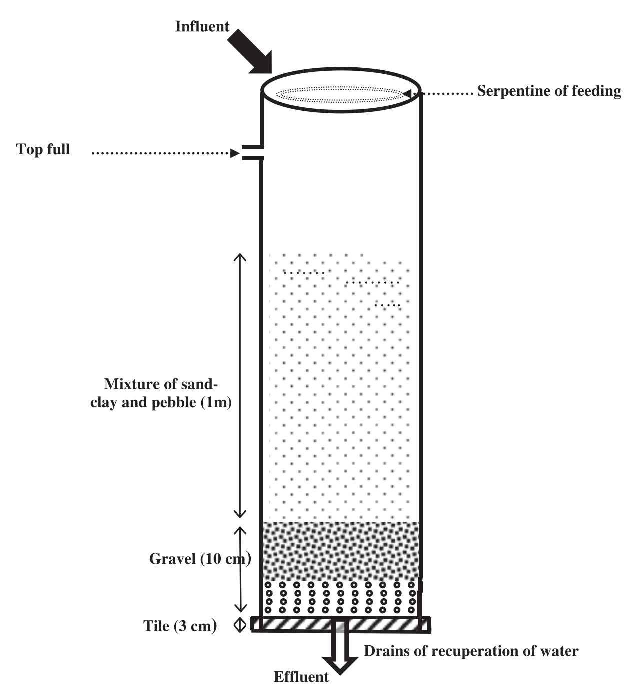

Fig. 1. Scheme of filtration column.

2.2. Characterization of sand and clay samples

The mean grain size of sand is 0.7 and the uniformity coefficient of the particle size distribution (d_{60}/d_{10}) is 1.25. For the geochemical studies, clays samples were digested in a polypropylene bottle using a mixture of analytical grade concentrated $HClO_4$ and HCl (in the ratio 3:2:1). The elemental analysis of the digested solution was carried out using atomic absorption. The oxides elements analyzed are shown in Table 1. The mineralogical and geochemical analysis of sand and clay was carried out by using a Diano 2000* EX-ray diffractometer. X-rays were produced by a copper anti-cathode tube ($\lambda = 1:54$ Å). Computer software XSPEX Version 5.41 was used in the interpretation of the diffractogram obtained.

2.3. Wastewater sampling technique

Wastewater samples used for the study were collected from Khenguet Elhojjej rural station in the northeast of Tunisia. The influent consisted of domestic wastewater (from toilet, kitchen, bathroom, etc.). The sewage quality of rural wastewater fluctuated greatly during the operation period as it was affected significantly by consumption of water. After decanting, wastewater sample was collected in 4 or 5 plastic sterile containers each with a volume of 20 L brought back to the laboratory and stored at 4˚C. To get a representative sample, we sampled 5 L per hour to put in each container; the total sampling time was 4 h. A single composite sample was made by mixing together all the collected samples and analyzed within 24 h.

2.4. Analysis

The pH and the dissolved oxygen (DO) were measured as recommended by the standard methods [14,23]. Analysis of various bacteriological parameters was started as soon as the samples were brought into the laboratory. All the samples were analyzed for DO, chemical oxygen demand (COD); biological oxygen demand (BOD); total Kjeldahl nitrogen (TKN); ammonium nitrogen (NH_4^+–N); nitrate-nitrogen (NO_3–N); fecal coliform (FC); fecal streptococci (FS); and total bacteria (TB) [23]. The results were given in Table 2.

Table 1
Centesimal compositions in M_xO_y oxides of the elements contained in the sample of raw and purified clay expressed in % mass

Constituent elements (% mass)	Samples	
	Raw clay	Purified clay
SiO_2	56.61	52.93
Al_2O_3	18.28	19.17
Fe_2O_3	6.21	7.04
CaO	1.17	0.12
MgO	1.33	1.74
K_2O	0.87	0.92
Na_2O	0.15	1.45
PF	14.38	16.63
Total	99	100

2.5. Permeability efficiency studies

Studies were conducted to determine the residence time of the wastewater in a series of columns (column used are 10 cm longer and 7 cm in diameter). Hundred ml of distilled water was applied to each nonfortified clay columns (0:1; 0.5:0.5; 0.66:0.33; 0.75:0.25; and 0.9:0.1 sand: clay) and fortified sand-clay columns (sand-clay/pebbles in ratio 3:1). The time taken to collect 20 ml from each medium was noted using a stop clock. The experiment was performed in triplicate and the mean value of the results was calculated and taken by time (t). The flow rate (Q), expressed as the volume of liquid passing through per unit time, was determined using the formula:

$$Q: V/t \quad (1)$$

where V is the volume of liquid (20 ml) passing through the system during time, t (s).

3. Results and discussion

3.1. Sand and clay characterization

The grain size analysis of the sand shows that it was medium sand (0.1 cm), the fine fraction was

Table 2
Results of raw and treated rural wastewater using infiltration percolation process

Parameter	Units	Raw sample	Treated sample	Removal rate (%)
pH		7.35	6.9	–
DO	mg/l	0.9	4.3	–
COD	mg/l	725	192	73.5
BOD	mg/l	369.3	91.5	75.2
NTK	mg/l	23.7	7.93	66.54
NH_4^+	mg/l	153	54.2	64.55
NO_3^-	mg/l	0.93	4.62	–
C.F.	CFU/100 ml	9.24	8.47	8.3
S.F.	CFU/100 ml	8.32	4.32	48
T.B.	CFU/100 ml	9.26	7.18	22.5

negligible (Fig. 2) and the semi-logarithmic curve determines that this sand was in the range of the sands used for the infiltration percolation given by the inter-agency [24] survey. The mineralogical analysis by the X-ray shows that it was quartz sands (Fig. 3).

The interpretation of each diffractogram obtained from the X-ray diffraction (XRD) analysis revealed the mineralogical assemblage of the clays used for the study. The percentage composition of the clay was presented in Fig. 4. Cation exchange capacity for the raw natural smectitic clay, determined by the copper ethylene diamine [25], was 39.49 meq/100 g. The values of the specific surface areas of the clay sample, S_{BET}, calculated by the BET method [26] were equal to 221.85 m^2/g for natural smectite clay used. For purified clays, these values can be significantly higher [27], but the choice of raw clay aims to minimize the cost of infiltration percolation process that can be subsequently used on large scale. The results of the geochemical analysis in Table 1 show the abundance of SiO_2, $A1_2O_3$, and H_2O^+ in the clays and, possibly, free silica that originated from siliceous microfossil, such as radiolarians and diatoms [28]. Fe_2O_3 is a significant impurity found in the clay investigated, though it was higher in our sample. The higher percentage of Fe_2O_3

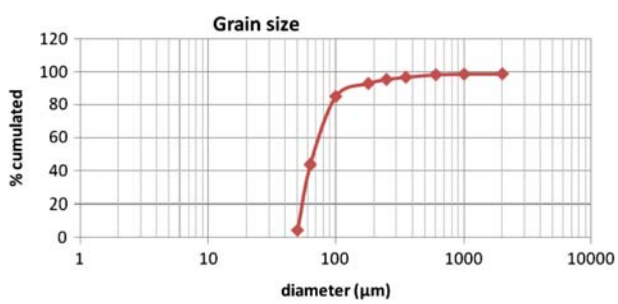

Fig. 2. Grain size of used sand.

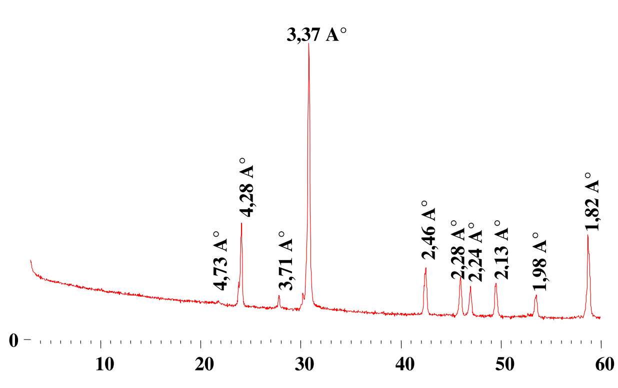

Fig. 3. XRD spectrum of sand.

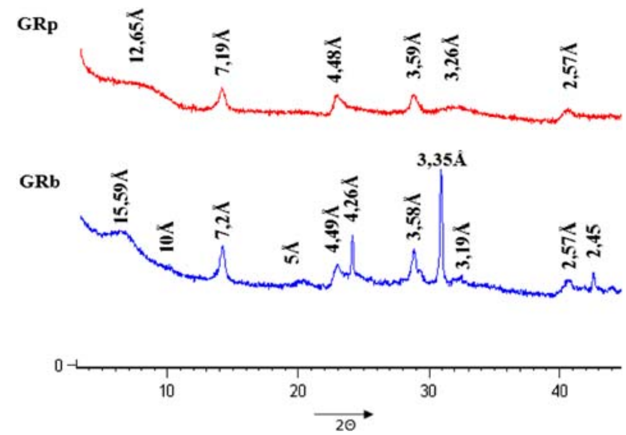

Fig. 4. XRD spectrum of natural clay, GRp: purified; GRb: raw.

could be ascribed to the presence of hematite in the mineralogical components. The percentage composition of MgO and CaO was relatively low in the clays.

3.2. Permeability study

The clay minerals found in the raw clay sample investigated were kaolinite, illite, and smectite. Swelling reduces the pore spaces in clay structure, which in turn affects the permeability to solvents. The higher swelling rate of raw clay type when soaked in water, results in a lower permeability and therefore higher residence time. Clay types Grombalia contained smectite, as a principal mineral, hence the low permeability and the longer residence time exhibited; this natural clay was added in some proportions, and the percentage of 10% in the sand filter assures the appropriate permeability for the process of infiltration percolation to ensure the everlastingness of the system (Table 3).

3.3. Wastewater treatment study

Two types of CEC have been identified in clays: permanent and pH-dependent CEC [29]. Permanent CEC is due to isomorphic substitution and it predominates at pH below 6, while the pH dependent predominates at a pH above 6. During the cation exchange reactions, alkali earth metals and hydrogen ions can exchange for cationic pollutants in the aqueous phase. It can be concluded that the pH-dependent CEC predominated in the treatment of rural wastewaters as a consequence of their high pH, which enhance the hydrolysis of the OH group at the broken crystal edges. When the OH is hydrolyzed, hydrogen ion is released into the water and caused a reduction in pH values (Fig. 5). Schulthess and Huang [29] assumed

Table 3
Results of permeability studies (pebble: sand/clay ratio 1:3)

Mixture sand/clay	Mean permeability (m/s)	
	Non fortified	Fortified
0/1	6.70×10^{-9}	3.13×10^{-7}
0.5/0.5	9.66×10^{-7}	2.68×10^{-6}
0.66/0.33	4.78×10^{-6}	6.50×10^{-6}
0.75/0.25	3.54×10^{-6}	9.20×10^{-6}
0.9/0.1	2.18×10^{-6}	2.29×10^{-5}

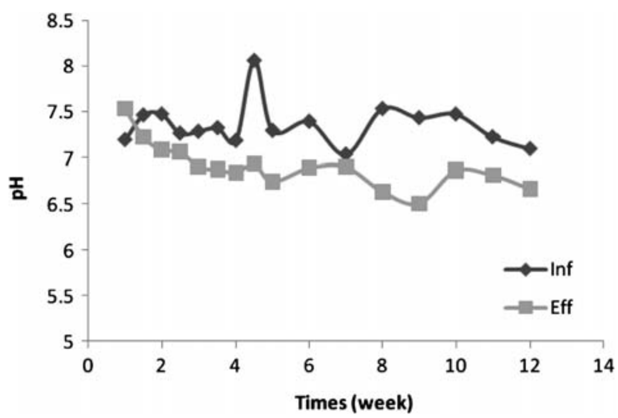

Fig. 5. Evolution of pH at the time of treatment.

that the pH-dependent charges are located on hydroxyl groups formed on the broken crystal edges.

Oxygen is renewed in the porous medium by introducing atmospheric fresh air through the infiltration surface and, possibly, by exchanges through the permeable boundaries of the bed (Fig. 6). The wastewater prevents gas exchanges at the base of beds lying on a draining gravel layer. Convective movements of liquid and gas phases are directly linked to the variations of the water stock in the infiltration profile.

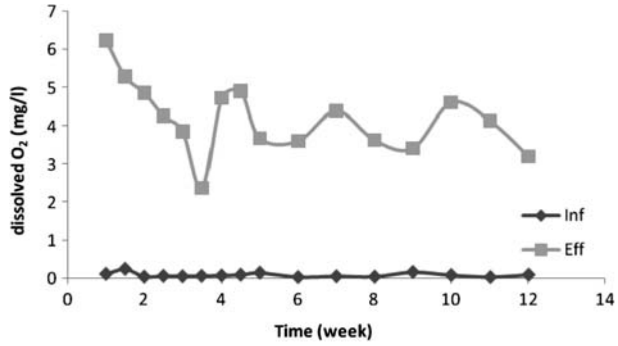

Fig. 6. Evolution of dissolved oxygen.

The values of the dissolved solids, also known as filterable solids, were still appreciable in amount in the effluents from column (3.2 mg/l) possibly due to the presence of some hydrophilic colloids, e.g. soluble proteins, protein degradation products and bacteria that passed through the percolator. Contributions could also be from some of the clay particles that are leached out of the column and some of the exchangeable cations leached from the exchangeable sites.

An overview of the COD and BOD reduction potentials in effluent shows that they were above 73 and 75%, respectively, in the experiments using column (Fig. 7). These mean values of COD and BOD in influent were respectively 725 and 370 mg O_2/L; the mean values in the effluent were 192 and 92 mg O_2/L, respectively, these results are lower than those obtained from previous works on on-site wastewater treatment methods using different on-site materials as percolator [22]. These lower results were due to the absence of biofilm because the sand was virgin and the biofilm had not yet formed and the mechanism of purification is only due to the adsorption and the precipitation. Characteristically, clay minerals were extremely fine-grained, possess a large surface area which ensure high adsorption and were closely packed, thereby acting as the primary barrier to organic pollution. For example, the swelling capacity of smectite is higher than kaolinite and illite because of the presence of expanding lattices in the structure of smectite. This and other smectite characteristics (e.g. high CEC) resulting from isomorphic substitution that are abundantly fulfilled in this mineral were thought to be responsible for the quality of effluents obtained from column.

There is a relationship between the DO and COD of the wastewater. An increase in the value of COD showed a corresponding reduction in the DO as observed in the study of Oladoja [22]. This increase varied from sample to another and could be attributed to different factors. The exhaustion of the exchangeable and adsorption sites with time and subsequent release or escape of some of the pollutants into the wastewater matrix which in turn depleted the DO [30].

It is known that water does not percolate through clay easily. As sand-clay was meant for use in the study, it has to be fortified with pebbles to facilitate water percolation; this mixture gives an appropriate permeability (2.29 cm/s) and inhibits the clogging of column for a long time. In three months of treatment, we do not note a decrease in the permeability and the purification performance increases with time. Aside from their function as a percolation aid, the pebbles also acted as an inert media for microbial attachment and growth [31].

During the transit through the percolator, the wastewater is purified by physical (filtration, adsorption) and biological (microbial degradation) processes. Adsorption and ion exchange are the principal physicochemical surface reactions that occur on clay during the transit of wastewater through this medium. Pollutants, in their ionic forms, are either exchanged for the exchangeable ions on the clay surface or get adsorbed on broken edges of the clay particles.

The oxidation of dissolved organic matter and oxidized nitrogen NTK is achieved as far as the oxygen required is available in the air phase of the porous medium. Two factors can be easily artificially regulated during the process of oxidation. One is the oxidation-reduction environmental characteristics of sand filter, and the other is the ratio of carbon to nitrogen [32]. The required amount of oxygen is defined as the total oxygen demand, the mass of oxygen consumed, in mg per liter of influent. During the aerobic percolation, DO and residence time should not be limiting factors. The total nitrogen removed by the fortified sand-clay columns was above 66%. This is almost the same results of studies got by other workers on onsite treatment systems for wastewater treatment [33] with the same flow rate. About 62% of TKN was removed when Kamppi [34] used ditched peat land to treat wastewater. The least reduction of the NH_4^+–N in the sand-clays studied was about 65% in this study. Adcock et al. [35] reported 93.2% reduction in their study using reed beds; after the fifth week, the removal of the total and ammonium nitrogen is better and it was due to the development of biofilm.

In our study, the content of NO_3–N reached 8 mg/l (Fig. 8), either a concentration superior to the entries of nitrogen in the filter. This quick start of the nitrification is normal because the filter is already showed and the biofilm is formed in sand filter. It is known that nitrifying bacteria are sensitive organisms and extremely susceptible to a wide variety of inhibitors such as high concentrations of ammonium and nitrous acid, low DO levels (<1 mg/L), pH outside the optimal range (7.5–8.6) [31]. Ammonium removal was not completely balanced by nitrate production, meaning that some denitrification had occurred [2].

The results obtained from treatment system showed that the removal of fecal coliform was 0.7 Ulog, fecal streptococci was 4 Ulog, and total bacteria was 2 Ulog (Fig. 9). After five weeks of continual functioning, the output is better and growing with only one feeding per week to achieve less than 10^3 CFU/100 ml. The performance of the fortified sand-clay in this study was due to the fact that bacteria behave like charged particles and so could be adsorbed on the clay surfaces and the most important is the increasing of germs removal with time. In fact it has been stated that owing to the functionality of certain chemical material comprising bacteria cell walls, bacteria exhibit surface charges similar to colloids [36].

Disinfection performances were relatively disappointing because of a too high debit value and heterogeneous infiltration. Also at the beginning of our test (five week), poor bacteriological performances were due to the absence of the biofilm that was not fully formed. Our fortified sand-clay was virgin and this will influence the flow and especially the residence time of rural wastewater into the sand-clay filter. Low removal occurs when water residence times in the sand filter are low [7]. After one month of continual functioning, the treatment efficiency has increased and therefore gives the levels of germs much lower in the treated wastewater (less than 10^3 CFU/100 ml). The process of infiltration through the soil improves strongly the quality of the water and it is likely that

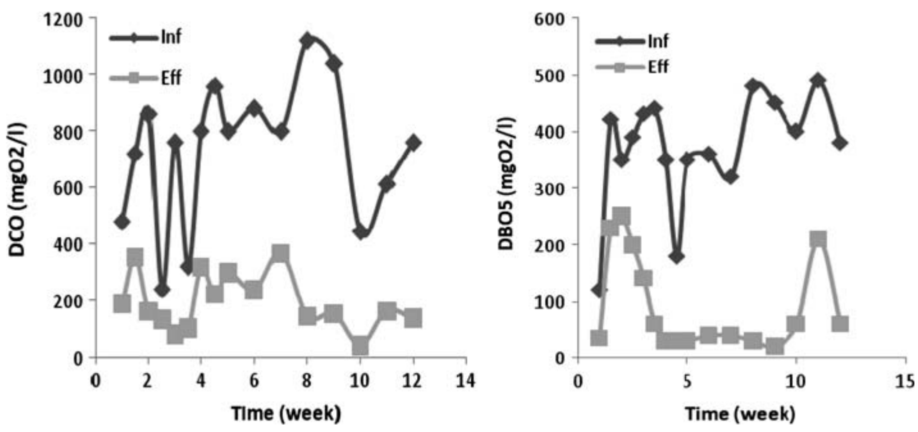

Fig. 7. Evolution of COD and BOD before and after treatment.

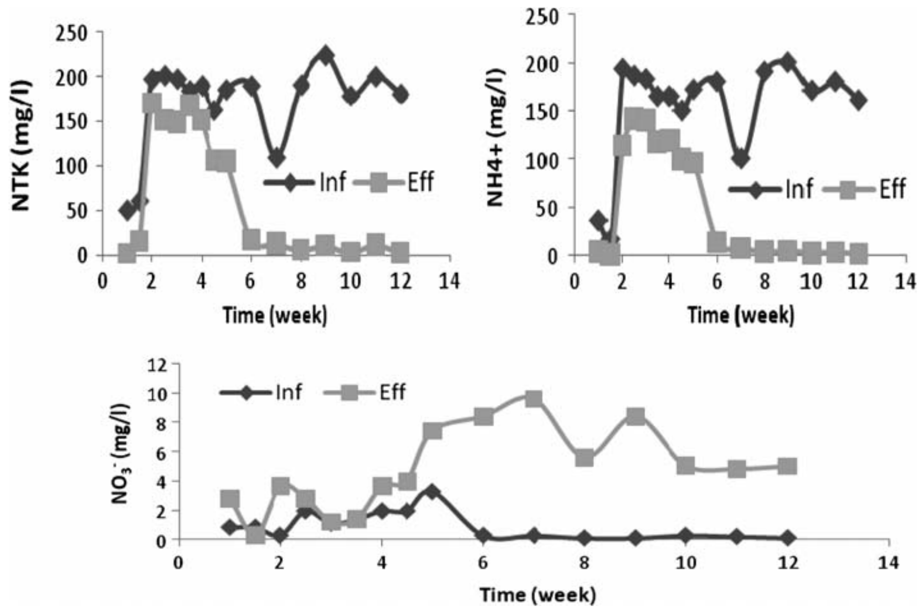

Fig. 8. Evolution of the different shapes of nitrogen before and after treatment.

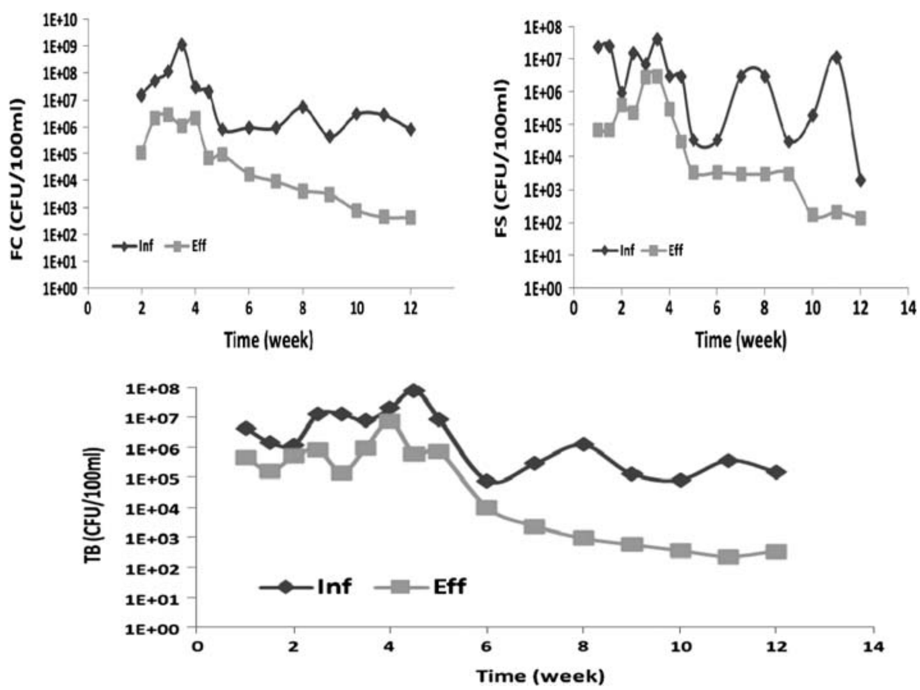

Fig. 9. Removal of the fecal coliform (FC), fecal streptococci (FS), and the total bacteria (TB).

most microorganisms are retained in the first few centimeters of the soil and either degraded or irreversibly adsorbed [37].

The amount of total bacteria in effluent from column was decreasing with time during the entire period of study (7.18 CFU/100 ml). Stone-pebbles were used for fortified to enhance water permeability, but the pebbles also present as an inert surface for microbial growth and attachment as obtained in trickling filters (a conventional biological method of sewage treatment) [22]. Therefore, microorganisms are partially retained in the system as the wastewater is passing through [36,37]. The retained micro-organism helped in both the aerobic and anaerobic digestion of the biodegradable fractions of the solid, which accounted for the reduction in the amount of TS (total solid) with time. But the most important thing is to modify the structure of the clay, at the time of the formation of biofilm; the interaction of the micro-organism with clay give a contraction suited by an expansion in the layers of the swelling clay and facilitates the oxygenation of the sand filter.

4. Conclusion

Based on the findings of this study, it can be concluded that sand-clay, fortified by pebbles, filtration can be used for rural wastewater treatment. This reconstituted sand filter is efficient for further removals of COD, BOD, microbiological contaminants, and nitrogen by adsorption on clay. The presence of clay provides the formation of biofilm in sand filter which improves the exhaustion of different analyzed parameters. The results of this 3-month study confirm that simultaneous adsorption and biological purification processes occur within the filter bed.

The results of various analyses carried out on raw and treated wastewater samples using fortified sand-clay columns (1 m sand filter depth) show that clays have high potential for rural wastewater treatment. The treatment efficiency is directly related to the mineralogical assemblage and the loading rate. The results show that fortified sand-clays have the potential to remove contaminants from rural wastewater, but further pilot-scale studies are required to determine long-term effectiveness of the media and to further develop the technology.

Effluent quality from the sand-clay filters at the low bed depth of 1 m and high filtration rate demonstrate that the sand-clay filter can be effectively used for secondary wastewater treatment for simultaneous removal of organics and nitrogen. This is of particular importance to developing countries that do not have the resources to readily avail themselves of cutting-edge mechanical secondary treatment systems, and undertake significant modifications of existing processes. This study demonstrates that a primitive passive technology such as sand-clay filtration following the widely used extended aeration, can achieve superior effluent quality.

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