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A study of columns to reduce mineral and biological pollutants during recharge operation by treated municipal wastewater

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ABSTRACT

One of the most important methods for reusing treated wastewater is soil aquifer treatment (SAT). For simulation of SAT pounds, three columns of 30 cm in diameter and 250 cm in height were filled with sandy loam soil and used to assess the removal of chemical and biochemical oxygen demands (COD and BOD), nitrogen, phosphate, total dissolved solid, total coliform, and fecal coliform from treated wastewater. The soil surfaces of columns were covered by different materials; one by geotextile, another by coarse structural debris, and the third one remained bare. These columns were saturated by treated wastewater from Mahdasht–Karaj treatment plant. All of the experiments were conducted under permanent saturated soil condition. The removal percentages of geotextile soil column were 84.7, 77, 67.7, 99.5, 99.7, and 79.9 for BOD, COD, TSS, coliform, fecal coliform, and phosphate, respectively, and low efficiency for nitrate removal in all columns. Also it was observed that more waterlogging time leads to a decrease in pollutant removal. Using geotextile and structural debris as soil surface covers will lead to a reduction in pollutants transfer and help in stabilizing the soil system as a filter.

Keywords: Biochemical oxygen demand; Chemical oxygen demand; Removal efficiency; Soil aquifer treatment

1. Introduction

Healthy life in a modern society is certainly dependent on providing high-quality water. Increased population will lead to surface and underground water pollution. Meanwhile, excessive usage of water will put renewable and underground water resources under pressure. Moreover, non-uniform distributed water resources and periodic droughts increase the needs for better use and water recources conservation. Population growth ensures the increased volume of treated wastewater that can play a reliable role to supply agricultural water according to their fixed rate of flow [1]. An effective approach to decrease wastewater pollutants is to put it into the soil which can be done through different ways, such as low-rate irrigation systems [2], flow through arid soil system [3], quick infiltration system [4], sandy filtration [5], soil infiltration system [6], and periodic

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sand filter [7]. Soil aquifer treatment (SAT) with treated wastewater is a low-cost approach for improving treated wastewater quality for drinking or other consumptions [8,9]. Municipal wastewater will infiltrate the soil from the bed of the pools and by passing through the unsaturated and saturated zones, physiochemical and biological reactions occur which will result in decreasing the amount of organic and inorganic matters, such as nitrogen, phosphate, TDS, and heavy metals [9–11]. The combination of wastewater and underground water and the slow pace of passing through the aquifer, adds to the contact time which will lead to improvements in water quality [12,13]. In a psychological view, SAT system is also important especially when the water pumped from the aquifer is used for domestic consumptions [12]. The most important factors that affect SAT efficiency are: soil properties, type of wastewater and treatment degree, topography, climate conditions, infiltration rate, and underground water depth. It also should be noticed that improper management of influents can lead to water recourses pollution, especially underground water, soil, and plant [14]. The main problems of wastewater artificial recharge basins are clogging and reduction in surface soil infiltration occurring because of suspended solids and biological closure of soil pores through time which can slightly be solved by scratching the soil surface [15].

Many research projects have been conducted to evaluate soil performance in pollutant reductions. Lance et al. [16] compared the removal amount of pollutants for primary and secondary treated wastewater using soil columns. Their results showed that nitrate removal from the wastewater with primary and secondary treatments were 45.6 and 28.5%, respectively. The reasons for better nitrate removal were either intense denitrification in wastewater with primary treatment because of high concentration of organic matters or high proportion of C/N. Their last results showed that the type of wastewater did not influence phosphate and fecal coliform removal. Powelson and Gerba [17] investigated virus transfer via soil columns using secondary treated wastewater and concluded that virus removal in unsaturated zone is better than saturated zone of soil, and also the type of wastewater does not influence virus transfer. Rice and Bouwer [18] conducted a study on using soil columns for pollutant removal in primary and secondary treated wastewater and came to a conclusion that removal efficiency of nitrogen, phosphate, bacteria, and virus for columns with secondary treated wastewater was significantly higher than for other columns. Kanarek et al. [19] studied SAT in Dan Region, Israel and came to a conclusion that if wastewater passes through deep aquifer, BOD and TDS will be completely removed, and phosphate and nitrogen will be reduced by 50 and 99%, respectively. Quanrud et al. [20] and Vanderzalm et al. [21] reported that water quality improves by infiltrating the soil.

Artificial recharge in Iran is primarily dedicated to aquifer enrichment using low-quality water (saline water, marginal water, and floods) in artificial recharging wells or distributing floods over planes. There is no dependable information about practicing aquifer treatment with wastewater through artificial recharging ponds. Due to insufficient experiences in Iran, it was necessary to perform primary experiments to recognize and assess the main and effective parameters on this issue and pollutants which are mostly probable to transfer to the depth. The main goal of this research is to study and evaluate the effects of applying different management practices in order to improve the soil surface infiltration, lowering the amount of pollutants transfer of treated municipal wastewater, such as TSS, COD, BOD_5, coliform, fecal coliform, nitrate, and phosphate into shallow aquifers through time. Thus, the best choice for SAT can be made and the system's efficiency at preventing contaminant transfer to soil depth will be evaluated.

2. Materials and methods

A physical set involving three soil columns were built for simulating artificial recharge ponds in order to study and determine the amount of contaminants which are the most probable to transfer to the soil depth. Columns were cylindrical in shape, made of PVC, with 250-cm height and, an inner diameter of 30 cm, and the columns' bottoms were closed with lids and flanges. Before filling the columns with soil, the inner sides of the columns were covered with sand and glue to prevent preferential flow. In order to collect water samples through saturated soil profile, two perforated PVC pipes with 2.5 cm in diameter and32 cm in length were installed horizontally 1 m apart in each column (Fig. 1). A degreed cylinder-shaped reservoir with 70-cm height and 10-cm diameter covered with aluminum foil (to prevent light passing and biological activities) was used for each column. Using valves on the reservoirs, inlet flow to the soil column was balanced according to infiltration rate, so a constant hydraulic head was conducted on the soil surface.

All columns were filled with sandy loam soil from bottom up to 200-cm height. The final infiltration rate of the soil was 25 ml/hr. No consolidation was done to the soil in order to imply critical conditions. Over time, the

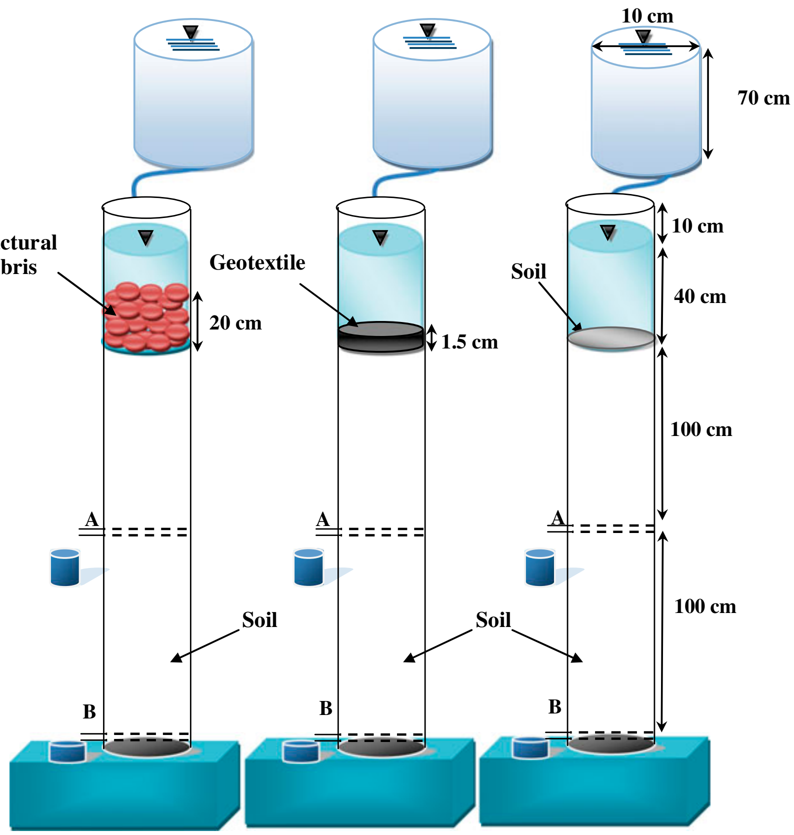

Fig. 1. A schematic of soil columns.

system's infiltration and efficiency reduce due to accumulation of particles on the soil surface, so three approaches have been performed to improve system performance. Two 1.5 cm thick geotextile sheets on the first column, 20 cm course debris of clay brick (with average size of 2 cm) on the second column and no cover (as a bare soil) on the third column were utilized. The materials were washed before use to remove anything clinging to them. The purpose of using geotextile and brick debris is to improve the conditions of soil infiltration and to increase the time that soil is used as a filter. The low cost and availability of the materials make it possible to replace or modify them whenever the infiltration rate decreases. Tables 1 and 2 show the physical and chemical characteristics of the soil, respectively.

For conducting the research, treated municipal wastewater was used and its characteristics are shown in Table 3. For better simulation of the actual conditions of recharge operations, the wastewater was flooding on soil columns permanently. At the start of the experiment, the depth of treated wastewater on the soil surface was 40 cm. Sampling from drains was done in five stages. The first sample was taken when the water outflow started from the drains and the others were taken by a 10-d interval. The samples were immediately transferred to laboratory to be analyzed for chemical and biological agents.

Table 1
Physical characteristics of the soil

Parameter	Amount
Sand (%)	58.50
Silt (%)	23.20
Clay (%)	18.30
Porosity (%)	0.41
Bulk density (g/cm^3)	1.54
Particle density (g/cm^3)	2.61

The analyzed parameters of inflow treated wastewater and outflow from drains of columns were BOD_5, COD, total coliform, fecal coliform, nitrate, phosphate, TSS, EC, and pH. The HACK (BOD track) device was used to analyze BOD_5. COD was analyzed with HACK (model45600) device. SP-7900 spectrophotometer was used for measuring nitrate and phosphate. pH was measured with pH meter and EC was measured with EC meter. The APHA[1] standard guidelines were

[1]American Public Health Association.

Table 2
Chemical characteristics of the soil

Parameter	Concentration
pH	7.95
EC (dS/m)	0.97
K (meq/l)	0.21
Na (meq/l)	3.50
Ca (meq/l)	7.30
Mg (meq/l)	3.00
Sum of cations (meq/l)	14.01
SO_4 (meq/l)	3.80
Cl (meq/l)	6.50
CO_3 (meq/l)	–
HCO_3 (meq/l)	5.00
Sum of anions (meq/l)	15.30
Sodium adsorption ratio $(meq/l)^{0.5}$	1.19
NO_3^{2-} (mg/l)	2.11
Organic carbon (%)	2.24

followed for conducting the experiments [22]. The mean comparison test method (*T*-Test) and SPSS software were used for performing statistical analysis.

3. Results and discussions

3.1. Changes in BOD_5 and COD amounts during recharge operations

Since BOD_5 and COD amounts are proper indicators of wastewater quality they have been measured. Mean of BOD_5 and COD amounts and range of inflow to soil columns and outflow from the first and second drains are shown in Tables 4 and 5.

It can be understood from Tables 4 and 5 that among all the columns, the geotextile-covered soil column had the best efficiency (significant at 5% level, $p < 0/05$) for reducing BOD_5 and COD amounts at both sampling points. Average (range) amounts of BOD_5 at the first and second drains (1- and 2-m depth from soil surface) were 13 (7–17.8) and 3.8 (2–7.1) mg/l, respectively. Average (range) amounts of COD at the first and second drains were 18.5 (15.5–21) and 10.7 (6–16.3) mg/l, respectively. The soil column with geotextile cover was the best for reducing contaminants with the highest removal percent of 84.7 and 77 for BOD_5 and COD. BOD_5 and COD removals by the soil column with structure debris were measured to be 77.5% and 72.1% and by the soil column with no cover were 70.4% and 67.3%, respectively. There was no significant difference between the column with structure debris and the one with no cover ($p > 0/05$). According to BOD_5 and COD amounts of the first drain in all columns, it should be mentioned that the most contaminant removal occurred at the top layer. This indicates that the topsoil could be considered as an efficient filter for removing contaminants. The studies done by Quanrud et al. [20], Cha et al. [23], and Grünheid et al. [24] showed the effective role of soil surface layer for reducing organic matters from sewage. Essandoh et al. [25] investigated contaminant removal from treated wastewater by soil column. Since BOD_5 and COD reductions in the soil are due to dissolved oxygen under aerobic decomposition conditions, upper 10 cm of the soil has the most amount of dissolved oxygen, and most of the BOD_5 and COD removals occur at this zone. Zhao et al. [26] studied pollutant removal from wastewater with soil columns on the laboratory scale and came to a conclusion that most of the organic matter removal occurs at upper 0.5 m of topsoil.

Total removal percentages of BOD_5 and COD vs. time are shown in Figs. 2 and 3. It can be understood that the soil column with geotextile had a better performance for reducing BOD_5 and COD amounts from wastewater and the soil column with structural debris had an acceptable performance for contaminant removal compared to the bare soil. The better performance is probably due to more physical filtration, increase in biological activities and decomposition, and absorption of live mass as biofilm on geotextile and structural debris on the soil surface. Carlson and Silverstein [27] observed similar phenomena results in their research around the sand particles.

It can be observed from the figures that 20 d past, the start of the artificial recharge, the amounts of

Table 3
Characteristics of the treated wastewater

Nitrate (mg/l)	Phosphate (Po_4^-) (mg/l)	Fecal coliform (MPN/100 ml)	Coliform (MPN/100 ml)	TSS (mg/l)	COD (mg/l)	BOD_5	Sampling time (d)
18.13	3.32	8.7×10^4	0.99×10^5	15.3	49	28	1
15.61	2.19	8.9×10^4	1.03×10^5	19.6	57	31	10
16.36	2.41	9.2×10^4	1.11×10^5	15.8	47	25	20
11.10	1.69	9.1×10^4	1.18×10^5	16.3	40	22	30
10.23	1.43	12.0×10^4	1.58×10^5	22.5	45	24	40

Table 4
BOD_5 values of the input treated wastewater and drained sample of artificial recharge columns

Soil surface cover	TW[a] (mg/l)		DS_1[b] (mg/l)		DS_2[c] (mg/l)		Removal of BOD_5 (%)
	Average	Range	Average	Range	Average	Range	
Bare soil	26	22.3–31.7	13.0	7.0–17.8	7.3	4.0–12.2	70.4
Geotextile sheets	26	22.3–31.7	9.6	6.1–11.8	3.8	2.1–7.1	84.7
Coarse debris of clay brick	26	22.3–31.7	12.8	9.0–16.1	5.6	4.1–8.3	77.5

[a]Treated wastewater.
[b]Drained sample (1-m depth from soil surface).
[c]Drained Sample (2-m depth from soil surface).

Table 5
COD values of the input treated wastewater and output of artificial recharge columns

Soil surface cover	TW[a] (mg/l)		DS_1[b] (mg/l)		DS_2[c] (mg/l)		Removal of COD (%)
	Average	Range	Average	Range	Average	Range	
Bare soil	47.6	40.1–57.3	21.8	17.6–25.3	14.9	9.2–21.8	67.3
Geotextile sheets	47.6	40.1–57.3	18.5	15.5–21.0	10.7	6.3–16.3	77.0
Coarse debris of clay brick	47.6	40.1–57.3	19.7	17.1–23.4	12.8	9.1–19.0	72/1

[a]Treated wastewater.
[b]Drained sample (1-m depth from soil surface).
[c]Drained Sample (2-m depth from soil surface).

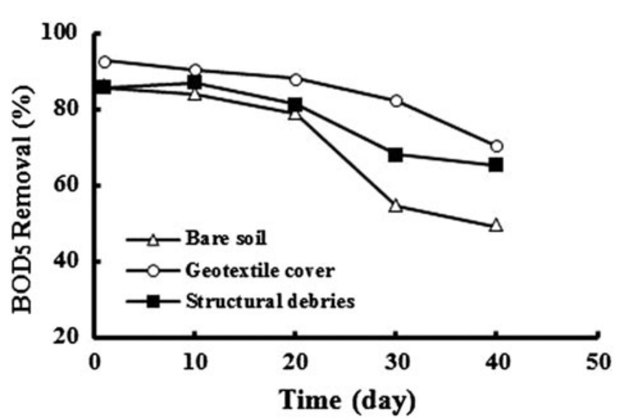

Fig. 2. Total BOD_5 removal percentage changes over time in the columns.

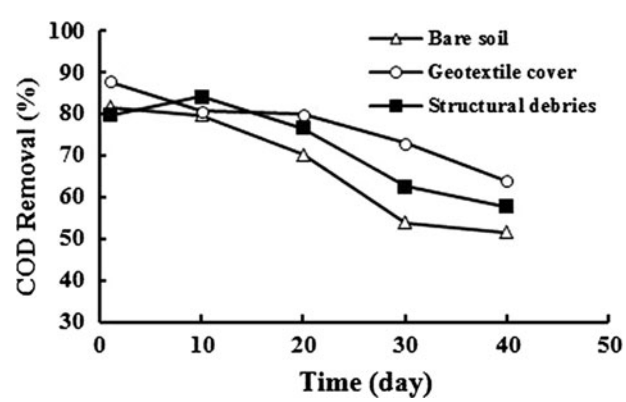

Fig. 3. Total COD removal percentage changes over time in the columns.

BOD_5 and COD from drains increased a bit and the most increase was observed on the column with bare soil. Reduction of organic matter removal over time is probably due to increase under anaerobic conditions of soil. Essandoh et al. [25] and Gray [28] stated that aerobic decomposition condition is more effective and faster at biochemical processes compared to those under anaerobic conditions, and the soil column with geotextile cover shows a better ability in removing organic matters over time.

3.2. Changes in transferred amounts of TSS at soil profile

Suspended solids are mostly organic matter that accumulate on the soil surface of an artificial pond in which only a small amount of them infiltrates in the soil. The average and range of TSS amounts in treated wastewater inflow and outflow samples are shown in Table 6.

The average TSS (range) of treated wastewater was 17.9 (15.3–22.5) mg/l in all of the columns. The geotextile soil column with an average removal of

67.7% had the most effective performance compared to other columns. The reason is that the small pores in geotextile act as a filter and prevent suspended solids to transfer into the soil column. Geotextile layer improves the removal of pollutants that are extracted through a physical mechanism. When pollutants are removed through a chemical-based mechanism, the geotextile layer does not have a significant effect. It is worth mentioning that physical absorption influences several chemical reactions such as BOD removal.

Soil column with structural debris and with an average removal of 51.1% had the lowest performance compared to other columns but it had no significant difference ($p > 0/05$) with bare soil treatment in contaminant removal. Most of the suspended solids removed by upper 1-m layer, because soil at this zone acts like effective filters which adsorb suspended solids in wastewater [29]. While most of the TSS removal occurs at upper meter of the soil columns with geotextile cover and bare soil, TSS removal was less in upper 1-m layer in the soil column with structure debris [20,30,31]. The TSS removal percentage vs. time is shown in Fig. 4. It shows that TSS amounts of outflow samples decrease with time until it reach a constant amount.

This situation is somewhat related to special conditions of the soil in the columns. Due to existence of the soil macropores, soil disturbance, and hydraulic changes of the soil, there is a possibility that the colloidal particles transfer in the soil profile and appeared in the outflow samples.

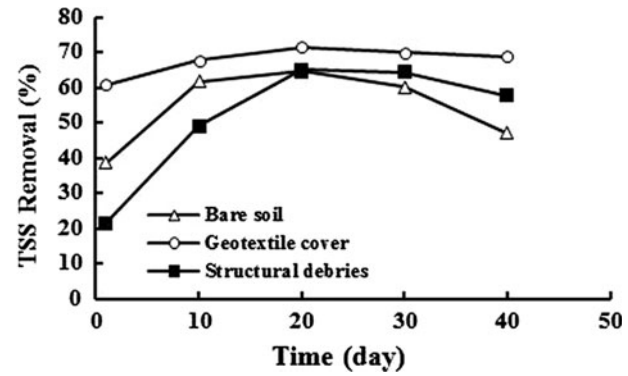

Fig. 4. Total TSS removal percentage changes over time in the columns.

3.3. Transfer of microbial agents into soil depth

Transfer of microbiologic agents to underground water that may occur because of SAT is of great importance since it is crucial in health aspects; therefore, it was studied in this research. To do so, the total coliform and fecal coliform numbers of inflow treated

Table 6
TSS values of the wastewater input and output of artificial recharge columns

Soil surface envelope	TW[a] (mg/l)		DS_1[b] (mg/l)		DS_2[c] (mg/l)		Removal of TSS (%)
	Average	Range	Average	Range	Average	Range	
Bare soil	17.9	15.3–22.5	11.3	10.1–16.4	7.9	5.6–10.9	55.3
Geotextile sheets	17.9	15.3–22.5	9.1	7.8–15.3	5.7	4.5–7.0	67.7
Coarse debris of clay brick	17.9	15.3–22.5	13.6	9.5–16.5	8.7	5.1–12.2	51.1

[a]Treated wastewater.
[b]Drained sample (1-m depth from soil surface).
[c]Drained sample (2-m depth from soil surface).

Table 7
Total coliform and fecal coliform amounts of the input and output of artificial recharge columns

Soil surface cover	Total coliform (MPN/100 ml)			Fecal coliform (MPN/100 ml)		
	TW[a]	DS[b]	Removal (%)	Tw	Ds	Removal (%)
Bare soil	1.2×10^5	2,445	97.9	9.9×10^4	1,320	98.3
Geotextile sheets	1.2×10^5	596	99.5	9.9×10^4	390	99.7
Coarse debris of clay brick	1.2×10^5	1,670	98.5	9.9×10^4	1,235	98.8

[a]Treated wastewater.
[b]Drained sample.

Table 8
Nitrate values of the input treated wastewater and collected sample of artificial recharge columns

Soil surface cover	TW^a (mg/l)		DS_1^b (mg/l)		DS_2^c (mg/l)		Removal of nitrate (%)
	Average	Range	Average	Range	Average	Range	
Bare soil	14.28	10.23–18.13	13.61	9.9–17.4	12.0	9.6–14.3	14.9
Geotextile sheets	14.28	10.23–18.13	12.76	8.9–16.0	1eded1.9	9.3–14.5	15.5
Coarse debris of clay brick	14.28	10.23–18.13	12.96	8.1–17.1	12.25	9.4–14.9	13.0

[a]Treated wastewater.
[b]Collected sample (1-m depth from soil surface).
[c]Collected Sample (2-m depth from soil surface).

wastewater and outflow samples from the second drains were measured. The results are shown in Table 7.

Table 7 shows that the soil column with geotextile surface cover had the best performance compared to other soil columns with removal of 99.5 and 99.7% for coliform and fecal coliform, respectively. It was observed that the soil columns with structural debris and bare soil also had a good performance for contaminant removal from wastewater. The ability to reduce pathogenic microbes can be referred to physical removal mechanisms that occur as the water infiltrates and intrinsic activity of micro-organisms [32,33].

The retention time that pathogenic microbes stay in soil is important since retention for a long time in soil may result in the deactivation of microbes [34]. From the high efficiency of total coliform and fecal coliform removals and low transferred amounts through columns depth, it can be concluded that by disinfecting treated wastewater and reducing amounts of biological pollutants and then using the water for aquifer recharge, the chances for biological pollutants to reach the underground water level, even in shallow aquifers, would be very low. There are various ways for disinfecting the treated wastewater. For instance, if the wastewater turbidity is low, the UV method can be used for disinfection. Caution must be exercised when chlorine or ozone are used since they might produce halomethane. They should be used in a way that low amounts of these chemicals remain in the water.

3.4. Nitrate transfer in soil profile and its changes

The amount of nitrogen that enters the soil is dependent to the amount of nitrogen in the wastewater and volume of the wastewater that is discharged to the soil. Because of the nitrate's negative charge, it is highly mobile in the soil and it will infiltrate to underground water and can be dangerous unless it is absorbed by plants and micro-organisms. The average

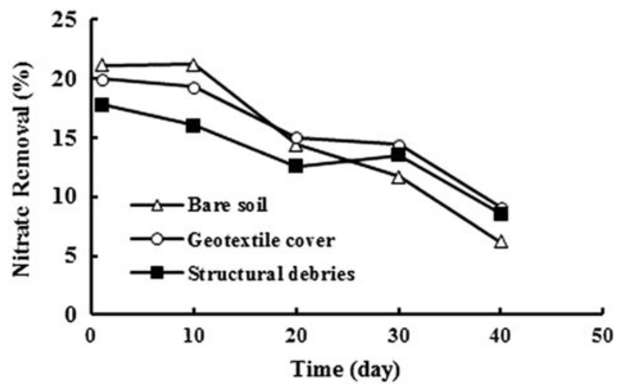

Fig. 5. Nitrate removal percentage changes over time in the columns.

and range of nitrate amounts in wastewater and collected samples are shown in Table 8.

It can be observed from Table 8 that all of the columns had the same amount of nitrate as inflow treated wastewater. For the entire soil columns, the nitrate reduction was low and the highest one was 15.57% which was measured for the soil column with

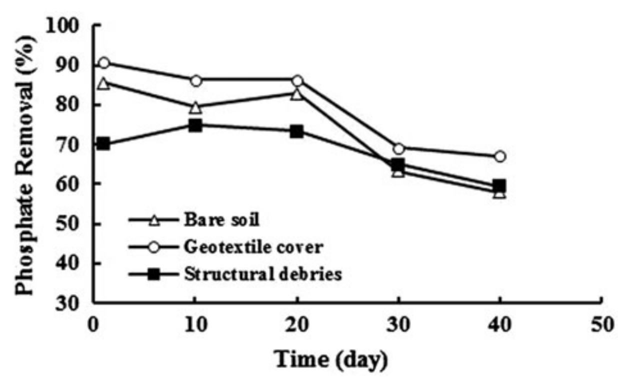

Fig. 6. Phosphate removal percentage changes over time in the columns.

Table 9
Phosphate values of the treated wastewater and drained effluent of artificial recharge columns

Soil surface cover	TW[a] (mg/l)		DS_1[b] (mg/l)		DS_2[c] (mg/l)		Removal of nitrate (%)
	Average	Range	Average	Range	Average	Range	
Bare soil	2.20	1.43–3.31	1.02	0.94–1.11	0.51	0.48–0.62	73.8
Geotextile sheets	2.20	1.43–3.31	0.86	0.75–0.96	0.38	0.30–0.52	79.9
Coarse debris of clay brick	2.20	1.43–3.31	1.05	0.94–1.21	0.67	0.55–0.99	68.6

[a]Treated wastewater.
[b]Drained sample (1-m depth from soil surface).
[c]Drained Sample (2-m depth from soil surface).

geotextile surface cover (which also did not have a significant difference with the bare soil column, $p > 0/05$). The nitrate reductions of the other columns were nearly the same. In other words, there was no noticeable difference for nitrate removal between all of the treatment approaches. The low nitrate reduction is probably because of nitrification in the soil. Possible options to improve the nitrate removal from treated wastewater in soil are to do some changes on the amounts of dissolved oxygen and carbon content so that denitrification will occur [35–37]. Nitrate removal vs. time is shown in Fig. 5.

It can be observed from Fig. 5 that as time passes since the application of treated wastewater, the percent of nitrate removal decreases in all of the columns. In other words, increase in outflow nitrate over time is because of decomposition and conversion of organic matters to nitrate.

3.5. Amounts of transferred phosphate to the soil depth

Phosphorus transfer to the soil depth happened in the form of phosphate. Phosphate is one of the main ingredients of eutrophication and if transferred to surface or underground water, the result will be the reduction in water quality. The average and range of phosphate amounts in the treated wastewater applied to the column and drain effluent are shown in Table 9.

As it is shown in Table 9, the geotextile column had the best performance of phosphate removal in depths of both samples. The average (range) amounts of phosphate in the samples taken from the first and second drains (1- and 2-m depth from soil surface) were 0.86 (1.43–3.31) and 0.38 (0.2–0.52) mg/l, respectively. Suzuki et al. [37] concluded from their research that soil have a high ability for removing and holding phosphate of wastewaters and a 25-cm height soil column, can remove phosphate up to 90%. Main reasons of phosphate holding by soils are adsorption of soil particles and phosphate sedimentation [38–40].

As shown in Table 9, most of the phosphate removal in all the columns, especially soil column with geotextile cover occurs in the upper 1-m layer. Fig. 6 shows the phosphate removal vs. time. Phosphate removal decreases as time passes and in the 30th day after the beginning of the experiment; the decrease is observed at all the columns, especially in the bare soil.

Bekele et al. [41] reported that as the time of discharging wastewater to the soil increases, the soil's phosphate adsorption ability decreases. Phosphate transfer in soil occurs when the soil reaches the maximum capacity of phosphorus adsorption [42,43]. So the soil phosphate adsorption capacity and immobilization should be studied in terms of using wastewater in soils.

4. Conclusions

The results indicated that soil has a high ability in reducing the amounts of TSS, BOD_5, COD, total coliform, fecal coliform, and phosphate during recharge operations. A high amount of nitrate from wastewater transferred to the soil depth and this can cause health problems, if it occurs to underground water. Using geotextile sheets and structural brick debris on soil surface had a high effect on contaminant removal, especially on COD, BOD, and TSS. Using geotextile is like a breakthrough since it significantly helped the soil, improving the treatments and it has not been used in Iran previously. This is more important when considering the current treatment technology in many developing countries, water treatment plants is not high and geotextile is easily available. The other benefits of using these kinds of materials were letting lower amounts of contaminants into the soil and expanding the time that soil can act as a filter. Due to availability and low cost of these materials, as the infiltration rate decreases, there is a possibility for change or enhancing the materials in order to improve the soil infiltration. It also should be taken into account that the experiment was conducted under critical conditions, such as soil type and wastewater discharge depth, and if the system is used under natural conditions, it undoubtedly will show better results. Considering the importance of the subject, more studies on this field of research will provide more precise information on the wastewater condition in soil and using this resource will reduce the environmental risks.

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