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Performance of hematite-grafted nonwoven geotextile layer for treatment of wastewater in SAT system: a columns study

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ABSTRACT

Urban wastewater is widely used around the world as a source of water, especially in arid and semi-arid areas. According to continuous municipal wastewater production through out the year and also due to prevention of environmental pollution, utilizing wastewater for artificial recharge is one of the most highly recommended methods. With respect to the processes in the soil vadose zone and subsequently in the aquifer, this method would improve wastewater quality and the so-called soil aquifer treatment (SAT). In this study, the recharge of urban wastewater in groundwater and also the effect of absorbent such as hematite-grafted non woven geo textile to increase the capacity to remove pollutants of this system were assessed. In order to perform the experiences and to control all conditions precisely, six SAT columns with an inner diameter of 20 cm and height of 2 m were used for 8 m. The columns were poured from sandy-loam soils and three absorbent layers to improve the reduction of pollutants. Its common practice was to operate SAT under a cyclic wetting and drying regime to simulate the real scenario. Applied management options include permanent flooding option as short-term periods (2-d wetting/2-d drying), medium term periods (7-d wetting/7-d drying) and long-term periods (14-d wetting/14-d drying).

Keywords: SAT; Hematite; Geotextile; Wastewater treatment; Artificial groundwater recharge

1. Introduction

Freshwater (FW) shortages are common in many countries in the Middle East and Mediterranean region due to long periods of drought, population growth, and the concomitant rise in water demand. The decrease in water resources coupled with an ever-increasing demand for water is a growing problem. Even with successful urban demand management and increased irrigation efficiency, new water supplies will be needed in future. Nearly half of the world's population depends on groundwater for drinking water and other uses (e.g. agricultural, municipal and industrial), and pumping often greatly exceeds the natural recharge [1–5].

Many water resource professionals believe that reclaiming water after treatment in a modern wastewater treatment plant has an important role in sustainable water resource management [6]. One of the most important methods of reusing treated wastewater is the soil aquifer treatment (SAT). The secondary treated wastewater (STW) is then further treated to the tertiary treated wastewater (TTW) by slow sand filtration using SAT. SAT is, essentially, a low-technology, advanced wastewater treatment system [7] The STW is allowed to be infiltrated vertically into a cell in the coastal groundwater aquifer through a sandy soil layer of about 15–30 m followed by horizontal flow through the aquifer to recovery wells located 1–2 km away from the infiltration basins. The long retention time of the STW in the soil facilitates biological activity, sedimentation, oxidation and reduction of viruses and bacteria and adsorption processes thereby improve effluent quality [8].

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Where soil and groundwater conditions are favorable for artificial recharge of groundwater through infiltration basins, a high degree of upgrading can be achieved by allowing partially-treated sewage effluent to be infiltrated into the soil and move down to the groundwater. The unsaturated or "vadose" zone then acts as a natural filter and can remove essentially all suspending solids, biodegradable materials, bacteria, viruses, and other microorganisms. Significant reductions of nitrogen, phosphorus, and heavy metals concentrations can also be achieved. It should be noted that several countries/areas in the Mediterranean region, including North Africa, which face the scarcity of FW availability, are currently using SAT projects to increase their water resources [9].

SAT has an excellent capacity of removing a wide range of contaminants by a variety of processes from the effluent. The soil-aquifer system should be viewed as a huge reactor in which both biological and physico-chemical processes occur. The biological and physico-chemical processes are performed in conjunction with one another. Consequently, the purification capacity is not affected by time. With proper operation and maintenance and adequate monitoring, the SAT system should be considered an extremely attractive and reliable method for effluent reclamation and reuse in areas where suitable conditions exist for groundwater recharge via spreading basins.

Soil aquifer treatment (SAT) or Management Artificial Recharge (MAR) technique involve water passing through both soil and an aquifer which combines their treatment compared with direct aquifer injection. The MAR system is deemed to be eco-friendly and economically efficient, and not only it effectively improves water quality but also offers low operational/maintenance costs (O/M costs) and energy use without any chemicals [10,11]. During the process, a variety of contaminants are removed by diverse reduction mechanisms, such as dispersion, filtration, biodegradation, adsorption, precipitation, ion exchange, and mixing with groundwater in the aquifer, the most common of which is biodegradation [12,13].

Treated wastewater (TW) is chemically different from FW, mainly due to its organic matter (OM) content. Representative OM contents, expressed in terms of chemical oxygen demand (OD), in raw sewage and primary and secondary effluents are: 250–1000, 150–750 and 30–60 mg/L, respectively [14,15]. The addition of OM originating from TW to soils can change their physicochemical properties. One of the physical effects resulting from TW application in soils is water repellency [16–19].

Recent studies have attempted to examine the removal of organic matter and nutrients from wastewater and surface water using the SAT system. However, few studies have investigated the use of absorbent in efficient removal of contaminants through experimental conditions. Besides, some drain pipes were placed through the soil column to investigate the exact amount of contaminant removal. Considering these pipes help to find appropriate place of the adsorbent layer in columns.

In this study, hematite-grafted non woven geo textile was used to investigate the removal of mineral and biological contaminants by sorption. Geo textile is a common material consisting of a permeable structure that possesses filtration and draining capacities [20]. Spychała and et al. examined the performance of innovative textile bio filters such as TS 50 and TC/PP 300 for domestic wastewater treatment and found them as a simple technology for removal of organic compounds and nutrients [21]. Experience with using geo textile filters to protect drains from clogging showed that geo textile filters attract biological colonization from liquids with a high organic content [22]. Cui showed that the surface modification method is feasible for improving the PP non-woven fabric's filtration efficiency [23]. The efficiency of the functionalized geo textile depends on the grafted biomolecule and this is why the choice of the biomolecule is crucial.

Up to now, iron oxide nano structures including nano particles, cubes, wires, and tubes have been extensively investigated for use in wastewater treatment. However, its practical application is greatly hindered because of slow charge transfer, a short hole diffusion length and a high probability of electron–hole re-combination [24]. Some work demonstrated that hollow structures could effectively alleviate the above-mentioned drawbacks since they often exhibited a highlight harvesting efficiency and a fast motion of charge carriers [25]. Hematite (a-Fe_2O_3) is the most thermodynamically stable iron oxide polymorph and, as such, is found globally within soil, water, and atmospheric systems [26,27]. Some studies on the sorption of contaminant using hematite were carried out. Elzinga and Sparks demonstrated phosphate adsorption onto hematite [28]. Xu and et al represented high removal capacity of Congo red in wastewater treatment by α-Fe_2O_3 micro flowers due to the high specific surface area and porous structure of hematite [4]. 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 [29,30]. In a psychological view, SAT system is also important especially when the water pumped from the aquifer is used for domestic consumptions [29]. 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 [31]. Knowledge of the evolution of geochemical processes in the soil is essential for the management of groundwater under artificial recharge regime. Laboratory-based soil column and batch experiments simulating SAT can improve our knowledge but they cannot accurately reproduce environmental conditions. On the other hand, it is difficult to interpret the results from studies at site scale because of our lack of control of the key parameters involved in these geochemical processes and the heterogeneities of the infiltrating system. In this study, column experiments were performed using real- field wastewater not spiked in the feed water. Feed water was filtered through a 0.45 mm filter before being used to reduce the effect of microorganisms. Chemical oxygen demand (COD), biological oxygen demand (BOD), nitrate (NO_3), and phosphate (P) concentrations were measured simultaneously with mineral concentrations. Therefore, the objectives of this study were to investigate the ability of the SAT system to attenuate target contaminants and functionalize textiles with hematite in order to decontaminate urbane wastewater.

2. Materials and methods

Functionalized polypropylene nonwoven (PP) geotextiles can be used as a new eco-friendly way to trap heavy metals in sediments. Hematite was chosen as sorbent because of its ability to remove environmental contaminants, its natural origin (from shells) and its low cost. XRF analysis of hematite is illustrated in Table 3. The hematite powder used in this experiment is from Toma Company located in Mahmoud Abad Industrial Zone in Isfahan. 157 mg of Hematite adsorbent was placed in geotextile according to ASTM D-5887 (absorbance capacity of 5 kg/m^2) and PVC transferring area.

The soil was firstly air-dried and then passed through a one-cm sieve. This helped to prevent the entrance of coarse clods and pebbles into the column when filling the columns. The exclusion of excessively coarse particles provides the possibility of more uniform soil, because the presence of excessively coarse pores creates preferential flow in the soil columns. Soil properties are indicated in Table 2.

Wetting and drying cycles are important for the intermittent application critical to long-term performance due to the fact that adding oxygen during the drying cycle, restores the infiltration rate, minimizes algae growth, promotes nitrification and denitrification and allows surface solids to dry. In this study 3 different time management, i.e., 2, 7 and 14 d of dry-wet cycling were investigated. The spatial and temporal evolution of the physical properties and chemical composition of water and soil during the infiltration of treated wastewater through a reactive soil column were investigated for 8 months.

To establish and non-moving columns, a metal table mesh with a height of 30 cm from the ground was used. Under each column, plastic containers were placed to collect drainage water. Also three drains were placed at depth of 10, 50 and 90 cm of soil columns to determine the rate of contaminant removal in the soil profile.

To fill the columns of the test, first it was poured by 15 cm of gravel in various sizes. In order to ban the soil, metal mesh was used at the end of the columns. Two absorbent layers in surface and 40 cm of soil columns were placed and also 35 cm was considered as a freeboard to add influent. By using the total volume of soil and soil porosity, sewage volume was calculated for the saturation of columns.

To enter the wastewater into the physical model, a plastic reservoir with a volume of 1500 L was used. The reservoir was placed near the perforated metal table. The wastewater was entered into the experiment columns in a rotatory form from the reservoir by a pipe with a diameter of 16 mm using a dropping pipe. Experimental pipes set-up and sampling tubes are shown in Figs 1–3. To settle the 40 cm fixed head on the columns, a water pump model 2MCP25/140 M (HP 1.5) and an on/off regulator (Shiva Waves WTB-30B model) was applied on the pump. Fresh wastewater was provided and transferred to experiment location during 15-d intervals.

To take samples of wastewater passing through the soil, at a 40 cm distance from the soil surface, holes with a diameter of 2 cm were dug out in the soil. Then, perforated PVC pipes with a diameter of 2 cm and a length of 40 cm which were prepared for sampling the wastewater flowing through the column were installed in them. The openings on the sampling pipes were placed in such a way that the area of each opening created in the pipe would be close to the area of openings on conventional common drainage pipes. After necessary examinations, two rows of holes

Fig. 1. PVC pipes and dropping pipe.

Fig. 2. Experimental pipes set-up.

Fig. 3. Sampling tubes.

Fig. 4. Sampling pipe.

were created in the pipes. Fig. 4 demonstrates a sample of provided drainages.

To avoid the ablution of soil particles by water flow and clogging of pores on sampling pipes, it is essential to coat them. With regard to the soft texture used in this study, two coatings of mosquito net and galvanized metal mesh were used around the drainages.

Finally, after the preparation of sample pipes, they were installed in the place of created holes in model hull in a way that the three drainages were placed in depth of 10, 50 and 90 cm from the surface. Then the locations of the sampling pipes were completely sealed by using adhesive for PVC pipes.

The hydraulic loading is divided into a flooding period as the 40 cm fixed head on the columns and a drainage period to allow the formation of aerobic conditions in the soil. The soil samples used in the experiment were collected from Tiran city in Isfahan province, Iran to be used in the column experiment. Soils were collected along the hillside, air-dried and sieved. The sand sieved methods were adapted from Oh et al. [32]. Column experiments were used for secondary effluents of the Isfahan University of Technology (IUT) Wastewater Treatment Plant in Isfahan. Water characteristics of influent were illustrated in Table 1. Influent water was used after 0.45 mm filtration during column experiments for removal of microorganisms in the influent water. Samples in all experiments were collected to investigate the removal of organic matter, COD, BOD, nitrate and phosphate by sampling tubes which are shown in Fig. 3.

Table 1
Water characteristics of influent

Parameter	IUT's TWW
BOD_5, mg/L	140
COD, mg/L	242
Coliform, MPN	460000
DO, mg/L	6.6
TSS, mg/L	544.93
pH	7.5
EC, dS/m	1.05
NO_3^-, mg/L	8.55
PO_4^{3-}, mg/L	2.10
Turbidity, NTU	55.83
Ca, mg/L	168
Mg, mg/L	44
Na, mg/L	84.9
SAR, $(meq/L)^{0.5}$	8.25

Table 2
Soil properties

Parameter	Soil sample
Sand, %	50
Silt, %	20
Clay, %	30
Bulk density, g/cm^3	1.5
Particle density, g/cm^3	2.65
Porosity, %	49.06
Hydraulic conductivity, mm/h	21.20
pH	7.5
Ec, dS/m	0.95
SAR, $(meq/l)^{0.5}$	1.19
Ca, mg/L	110
Mg, mg/L	90
NO_3^-, mg/L	10
PO_4^{3-}, mg/L	18.5
Na, mg/L	47.2
K, mg/kg	306.1
OM	0.25

2.1. Chemicals

2.2. Column experiment

This study was based by the randomized complete block design. Column experiments investigate the attenuation of organic matter and nutrients using Hematite-grafted non woven geotextile as an adsorbent in soil. Feed water was served by secondary effluent of IUT WWTP. Columns were used for 3 different time managements: 2, 7 and 14 dry-wet cycling. The blank experiment was also executed with the same feed water to investigate the loss of target contaminants during the experimental period. From the respective storage tank with a 1500 L capacity the inflowing water was pumped through the column with a pump (lucky pro, 2MCP25/140 M, HP 1.5, China) from top to bottom. PVC soil columns with an inner diameter of 20 cm and a length of 200 cm were used. The columns were packed with sandy-loam soils and one mentioned absorbent as the layers operating as a continuous liquid system. Operating temperatures were kept in 16–18°C. The temperature of wastewater storage before application was 23°C.

Table 3
XRF[1] analysis of Hematite (α-Fe_2O_3)

Compound	w/w %
Fe_2O_3	95.10
SiO_2	1.28
CaO	0.79
Al_2O_3	0.59
MgO	0.21
SO_3	1.71
Na_2O	<0.01
TiO_2	<0.03
MnO	0.25
LOI[2] (100°C, 2h)	1.64
Total	99.25

[1]X-ray fluorescence
[2]Loss on Ignition

2.3. Analytical methodologies

pH of water samples was measured by pH meter (laboratory-ph-meter-cp-505, Malaysia). To measure the EC, Wilhelm cond-3110, which has electrodes to correct temperature and measure the EC was used. Ca and Mg were measured by titration method with EDTA. Na concentrations was measured by flame photometer model Jenway- pfp7. Measurement of TSS was done by filter paper (diameter of 125 mm, 1–2 µm pore size) MUNKTELL purple. Results of turbidity measurement basis by NTU was reported. The drainage water turbidity samples was measured by turbidity meter model DRT-15CE.

A UV/VIS Spectrophotometer (JASCO Model V-530, Japan) was conducted to identify NO_3^- and PO_4^{3-}. COD of the samples was digested with a Close Reflux reactor and was quantified by the colorology method using Spectrophotometer (CG824, MILTON ROY). Incubation model FTC 90I was also used to obtain BOD5 of water samples.

3. Results and discussion

Table 1 shows the variation of pH, BOD, COD, Ca, Mg, Na, TSS, EC, Turbidity, NO_3^- and PO_4^{3-} in the TW. Samples were taken from each column system in the intervals of the column experiment during eighth months. During a comparison of the soil-adsorbent columns (H) and blank columns (C) systems, NO_3^- and PO_4^{3-} data showed that the H system had better removal efficiency than did the C system, that is, hematite-grafted non woven geotextile in columns could affect the removal of NO_3^- and PO_4^{3-}. After an eighth-months column experiment of the SAT systems, the NO_3^- concentrations had increased from drain 1 to drain 3 in both system except C system in 2 dry-wet cycles. The characteristics of nutrients and bulk organic materials in the feed and treated water, using the C and H systems, are shown in Figs. 5–15.

3.1. Nitrate changes (NO_3^-)

The amount of nitrogen that enters the soil is dependent on the amount of nitrogen in the wastewater and the volume of wastewater that is discharged into 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. In the feed water, the primarily concentration of nitrate was 8.55 mg/L. The removal efficiency of nitrate was 32% in the H system for 7-d time management. Hematite-grafted non woven geotextile layer which also did not have a significant difference with the control soil column ($p > 0/5$). 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 adsorption of nitrate ions was low in soil surfaces because nitrate ions are conservative in soil and the solubility of water is high [33,34]. To remove nitrate in saturated soil, assimilatory nitrate reduction or dissimilatory nitrate reduction (denitrification) occurs [35]. Presumably, this is due to the assimilation of nitrate, as it is unlikely that dissimilatory nitrate reduction would occur in the presence of oxygen [36]. It can be observed from Fig. 6 that as time passes since the application of treated wastewater, the percent of nitrate removal decreases in most of the columns. In other words, increase in outflow nitrate over time is because of decomposition and conversion of organic matters to nitrate. SAT system that was used in this study was not efficient for the removal of nitrate.

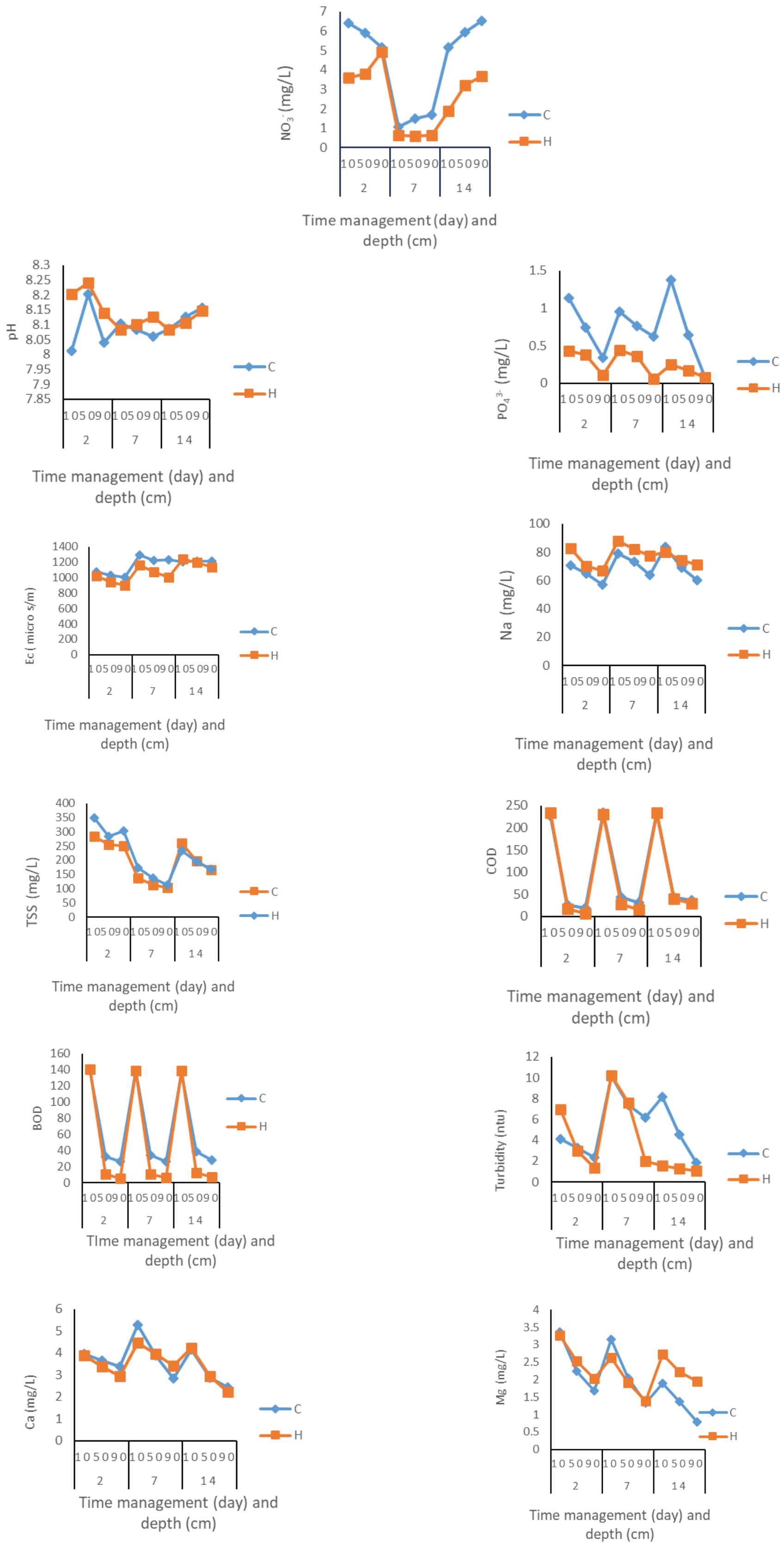
3.2. Phosphate changes (PO_4^{3-})

Phosphorus as a nutritional factor contributing to the phenomenon of Eutrophication which transmits it to surface and groundwater makes the degradation quality of them. Negligible amounts of phosphate was detected in the feed and treated water. Phosphorus could be mostly eliminated by either chemical precipitation reacting with ammonium, calcium, or magnesium or physical adsorption onto the minerals (Fe, Al, or Ca) [2,37–39]. It is also known that the removal of phosphorus is determined by the hydraulic loading rate [40]. If the renovated water is to be used for recreational lakes or discharged into surface water, phosphorus should also be removed to prevent algal growth in the receiving water. The P concentrations in the H and C systems had decreased by 94.78% in the H system for 7-d time management. The combination of chemical precipitation, physical adsorption and hydraulic loading rate eliminated the phosphorus due to the adequate presence of ions and the metal composition of the soil.

In order to evaluate the effects of contact time and hematite-grafted non woven geotextile layer on the sorption process, experiments were carried out at different times and three drainage depths. As shown in Fig. 8, the most of the phosphate in all the columns, especially soil column with geotextile cover occurs in the 1-m layer.

Figs. 5–15 represent the variation in sorption values with respect to time and drainage depth. Also, statistical analysis of this study is given in Table 4.

Using geotextile sheets on soil surface had a high effect on contaminant removal, especially on COD, BOD, Turbidity and PO_4^{3-} with removal rates of about 97%, 98%, 98%, and 95% respectively. In contrast, Na and, to a lesser



Figs. 5-15. Effect of contact time on adsorption of some contaminants onto Hematite-grafted nonwoven geotextile layer at different time management.

Table 4
coefficient of variation (CV) and R-Squared of parameters

Parameter	CV (%)	R (%)
NO_3^-	54.79	77.13
PO_4^{3-}	77.78	73.14
TSS	20.12	87.06
Ca	25.57	67.67
Mg	33.90	70.42
Na	15.2	70.71
Turbidity	57.65	81.79
EC	9.61	67.81
pH	1.98	91.65
COD	12.88	99.45
BOD_5	2.1	99.95

extent, Mg and Ca were released in the soil as shown by negative removal rates of −13%, −1% and –0.08, respectively. The pH was near neutral, ranging from 6.8 to 7.5 in treated wastewater and from 8.0 to 8.3 in output water. Also, the electrical conductivity (EC) ranged from 1 to 1.3 mS/cm in the treated wastewater and from 0.8 to 1.2 mS/cm in the output water.

4. The relevance of this experiment

With regard to Iran's position and its location on the arid and semi-arid belt, as well as the recent droughts, optimum use of water is a necessity. Adequate research has not been conducted in Iran on the use of artificial groundwater recharge with wastewater. This is a way for both wastewater treatment and the prevention of excessive reduction of groundwater level. The high volume of produced wastes necessitates further examination of this solution.

5. Conclusions

The following conclusions are supported by the experimental results obtained in this study regarding the water quality dependence of an SAT-treated effluent upon different time management and adsorbents in soil columns. Based on the removal results of organic matter and nitrogen within the SAT-simulated column experiments, the COD and BOD was found to effectively remove target contaminants during soil passage. The removal of phosphorus in column experiments was found to be dependent on the composition of soil (sorbent) and hydraulic loading rate. Based on the experimental results, sorption was found to be an important mechanisms for the removal of BOD_5, COD and turbidity within the SAT-simulated systems. Further study is required to increase the removal efficiency of nitrate and this finding demands more research.

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