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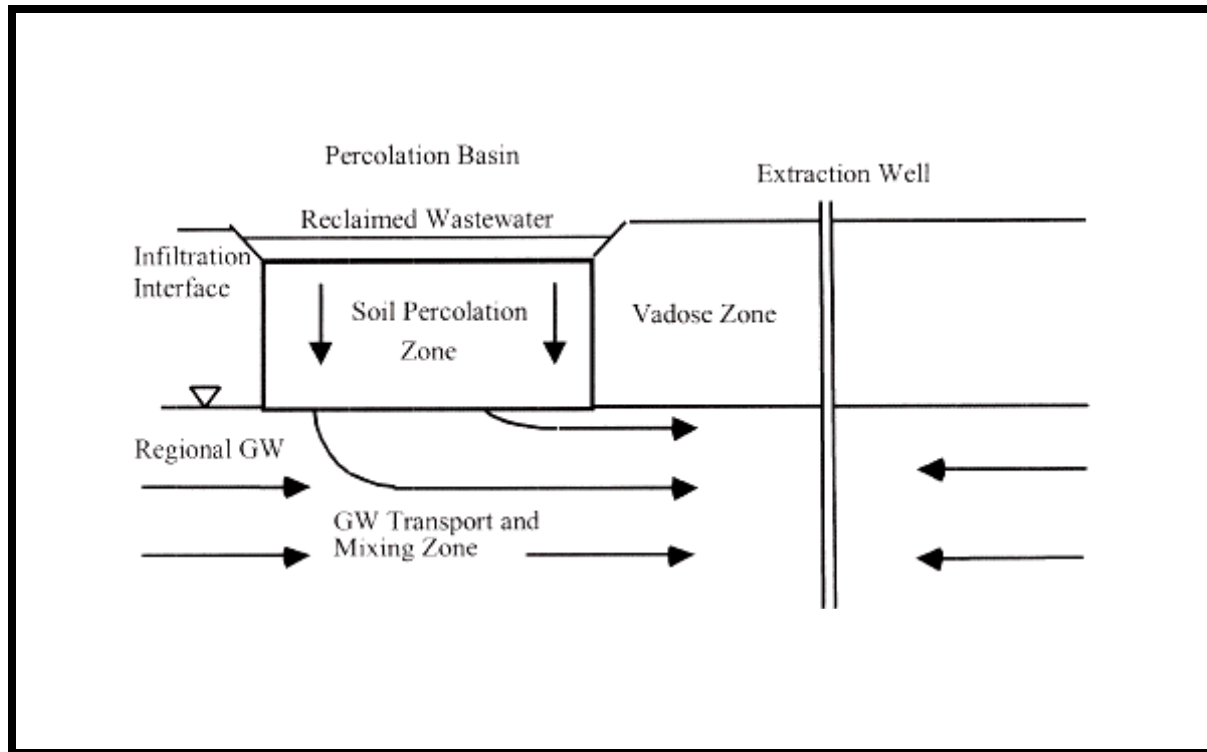
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UNESCO-IHE INSTITUTE FOR WATER EDUCATION



Analysis of removal of multiple contaminants during soil aquifer treatment

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Analysis of removal of multiple contaminants during soil aquifer treatment

Master of Science Thesis
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The findings, interpretations and conclusions expressed in this study do neither necessarily reflect the views of the UNESCO-IHE Institute for Water Education, nor of the individual members of the MSc committee, nor of their respective employers

Dedication

This Msc Thesis is dedicated to my wife Josephine, my son Baraka and the family of Mr. and Mrs. Enock M.H Chacha for their moral support and prayer during my study abroad

Abstract

SAT technology uses physical and bio-chemical processes in the soil matrix and aquifer to treat wastewater simultaneously recharging the aquifer. The application of SAT technology in arid and semi arid regions of the world where groundwater sources has been over exploited augments water supply. The recharged water is stored in the aquifer and then recovered for reuse especially indirect potable reuse. This is an attractive water management concept.

Many SAT studies have been carried out around the world for the removal of different contaminants but there are no system tools or models available for the prediction of the removal of different contaminants namely organic matter, trace organics, phosphorus, ammonia, nitrate or microorganisms at different process conditions during SAT. This tool is very important for the design and operation of SAT systems, it can also save time in decisions making. However, the design of SAT is based on judgment and experience. Understanding processes and conditions controlling the fate of different contaminants during soil aquifer treatment (SAT) and development of a tool for prediction of SAT effluent quality is the focus of this research.

This study was carried out by conducting extensive literature review on which relevant parameters influencing the removal of dissolved organic carbon (DOC), ammonia, nitrate, phosphorus, trace organics and microbes during SAT of primary, secondary and tertiary effluents were extracted. The parameters included travel distance, residence/travel time, pH, temperature, soil type, operating schedule, redox conditions and infiltration rates. The performance data for SAT (removal efficiency) with respect to travel distance and travel time were analysed after grouping them in bins. The first step was to do correlation analysis of different parameters on DOC removal. DOC was chosen because it has influence on removal of other parameters such as ammonia and nitrate. The correlation analysis matrix showed a weak correlation among the parameters involved which suggested that SAT is case specific. The data were analysed further to find contaminant removal range, average and standard deviation on each bin. Three separate sets of guidelines were developed for estimation of removal of DOC, nitrogen species, trace organics, and microbes from primary, secondary and tertiary effluent respectively. The developed guidelines could be useful as a quick tool in making right judgments for preliminary designs of SAT systems and time in doing pilot studies will be saved. Also a framework for transfer of SAT technology and application of SAT technology has been proposed.

The most interesting finding of this study is that the average DOC concentration of SAT product water in field sites was <2 mg/L for both long term SAT of secondary and tertiary effluent which is below the average DOC found in drinking water supply which is 2.2 mg/L. Therefore tertiary treatment prior to SAT may not be needed, though higher infiltration rate can be applied after tertiary treatment. In general, it can be concluded that SAT has the capacity to remove virtually all contaminants focused in this study from wastewater treatment plants effluents.

Key words: Soil aquifer treatment (SAT), travel distance, travel time, infiltration rates, adsorption, redox and biodegradation.

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List of symbols

APECs	Alkylphenol ethoxylates
BOD	Biochemical oxygen demand
BDOC	Biodegradable dissolved organic carbon
DOC	Dissolved organic carbon
DBPs	Disinfection by-products
EDCs	Endocrine disrupting compounds
EDTA	Ethyldiamine tetraacetic acid
NBDOC	Non biodegradable dissolved organic carbon
NCSWS	National center for sustainable water supply
NDC	Naphthalene Carboxylic acid
NTA	Nitrilotriacetic
PhACs	Pharmaceutically active compound
SAT	Soil aquifer treatment
SMPs	Soluble microbial products
SOCs	Synthetic organic compounds
THMs	Trihalomethanes

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1.0 INTRODUCTION

1.1 Background

The increasing scarcity of water in the world along with rapid population increase in urban areas provides huge challenge in urban and sanitation sector, especially in arid regions of the world. Groundwater storage formed by aquifers is invaluable for water supply and storage. However, natural replenishment for these aquifers is very slow. Artificial groundwater recharge using wastewater effluent accomplished through infiltration via spreading basin or direct injection is supply augmentation practice that is already used in some arid regions (Eusuff and Lansey, 2004). Types and quantities of contaminants of reclaimed wastewater as well as degree of pretreatment has to be assessed prior to surface spreading or injection to groundwater aquifers (Asano and Cotruvo, 2004). Infiltration and percolation through the soil improves reclaimed wastewater quality. Collectively, the water quality improvements that arise from percolation and groundwater transport and storage process are termed as soil aquifer treatment (Fox *et al.*, 2005).

Treatment of reclaimed wastewater during soil aquifer treatment (SAT) relies on biogeochemical processes in the soil (Lin *et al.*, 2004). Filtration, sorption and biodegradation processes in the soil can reduce or remove microbial and other contaminants in wastewater (Powelson *et al.*, 1993). Aerobic, anoxic and anaerobic conditions promote biodegradation of organic carbon under different electron acceptors in SAT systems. Dissolved oxygen decreases as wastewater percolates through the vadose zone and redox potential decreases, Nitrate becomes the next electron acceptor followed by iron or manganese (Fox *et al.*, 2001b). Bacteria are removed by filtration, predation, adsorption and the occurrence of adverse conditions (Katukiza, 2006). The removal of virus is controlled by number of factors, most important factors are type of soil, type of virus, infiltration rate and the degree of soil saturation (Quanrud *et al.*, 2003b). Viruses can be removed by adsorption during SAT. Human enteric viruses have low adsorption to soil and survive longer in the environment (Powelson *et al.*, 1993).

The treated wastewater during SAT is stored in the aquifer and then recovered for indirect potable reuse especially unrestricted irrigation. Subsurface storage provides a more economic and environmentally and socially acceptable option than a surface storage (Dillon *et al.*, 2006). A decision related to wastewater reuse should consider the aspect of hazards and benefits. Benefits are expressed when agriculture production is maintained and environmental quality and water sources are maintained (Haruvy, 1998).

Most of the projected global population growth will take place in third world countries that already suffer from water, food and health problems. Municipal wastewater can be an important water resource but its use must be carefully planned and regulated to avoid adverse health impacts (Bouwer, 2000). SAT systems are inexpensive, efficient for pathogen removal and operation is not highly technical and therefore attractive for developing countries in arid and semi arid regions. However, there is a limited knowledge about transport and fate of pharmaceutically active compounds (PhACs),

Endocrine-disrupting organisms (EDCs) and trace organic compounds like ethylenediaminetetraacetic acid (EDTA) and nitrosdimethylamine (Katukiza, 2006).

1.2 Problem identification

Reuse of wastewater to augment water supply presents a wide spectrum of health and technical challenges. A major concern is the presence of chemical and microbiological agents in wastewater that could be harmful to human health and to the environment. High loads of organic matter and ammonia nitrogen lead to dissolved oxygen depletion in water bodies and nutrient discharges may cause eutrophication (Brdjanovic, 2006). The organic compounds in wastewater are grouped into natural organic matter (NOM), synthetic organic compounds (SOCs), disinfection byproducts (DBPs) and soluble microbial products (SMPs) (Amy and Drewes, 2006b). Chlorine disinfection on water with dissolved organic matter produces disinfection by products (DBPs) trihalo-methanes (THMs). The organo-halide are suspected to be a human carcinogen (Quanrud *et al.*, 2003c). Wastewater treatment to remove or reduce contaminants including potentially harmful organic compounds is needed prior to indirect potable reuse. DBPs like THMs and halo-acetic acids (HAA) can be biodegraded during SAT (Drewes and Jekel, 1998).

SAT is a sustainable technology for wastewater treatment prior to indirect potable reuse. It is a low cost and operation is not highly technical and therefore suitable to arid and semi arid developing countries. Removal of pollutants during SAT is area specific requiring hydro-geological investigation before application of SAT technology. Determination of land requirement is also important in order to determine the type of infiltration and the pretreatment requirement prior to SAT. Wastewater constituents are transformed or removed by different mechanisms during SAT depending on process conditions, analysis of representative soil samples from different sites is needed to study several processes that occur during SAT (Fox *et al.*, 2005). Regulatory and policy requirements of a country have to be met for importation and operation of any technology. Health concerns related to the use SAT effluents can also affect the acceptability of SAT technology.

However, there are no tools available for the estimation of the removal of different contaminants namely organic matter, trace organics, ammonia, nitrate or microbes at different process conditions during SAT with respect to time-distance relationship without conducting pilot studies or extensive field investigation. Also the design of SAT systems is based on judgment and experience. Therefore, there is a strong need to develop guidelines which will help to make preliminary estimation or prediction of final water quality that could be obtained from SAT system. Guidelines for estimation of treated water quality for the given wastewater constituents during SAT would be useful for the design, analysis and operation of SAT system. Furthermore, such guidelines will be very useful in decision making for the acceptability of technology.

1.3 Goal and objectives

The main goal of this study is to develop tools to estimate removal of multiple contaminants from reclaimed wastewater during SAT by using results from batch tests, soil columns and site SAT collected from literature sources on SAT studies.

The following are the specific objective of this study:

1. To analyze the removal of organic matter, ammonia, nitrate, trace organics and microbes during SAT using different influent wastewater under different process conditions namely infiltration rate, redox conditions and pre-treatment based on literature review.
2. To develop guidelines for water quality estimation for removal of organic matter, ammonia, nitrate, trace organics and microbes from primary, secondary and tertiary effluents during SAT at different travel distance and residence/travel time.
3. To develop a framework for transfer of SAT technology

2.0 LITERATURE REVIEW

2.1 Overview on wastewater composition and treatment

2.1.1 Need for wastewater treatment

Wastewater treatment is necessary to protect public health and environment. Treatment of wastewater to remove pathogens prevents transmission of water borne diseases and therefore improving public health. In addition to removal of pathogens, appropriate treatment of wastewater protects the public from diseases that may be caused by heavy metals and potentially harmful organic compounds. The environment is protected from high loads of organic matter leading to prevention of depletion of oxygen and maintains or establish a health aquatic environment for flora and fauna (Brdjanovic, 2006).

Wastewater treatment provides opportunity for recovery and reuse of resources such as energy, nutrients and water achieved by the treatment process that makes possible reuse of water and side products (Gijzen, 2005). Reuse of wastewater is increasing due to scarcity of water and increasing urban population in many parts of the world, especially in arid and semi arid regions.

2.1.2 Municipal wastewater constituents

Municipal wastewater is mainly comprised of water (99.9%) together with relatively small concentrations of suspended and dissolved organic and inorganic solids. Major constituents of typical domestic wastewater are dissolved solids, suspended solids, nitrogen total (as N), phosphorus (as P), alkalinity (as CaCO₃), and chloride. Municipal wastewater may contain inorganic substances from industrial sources and domestic sources that includes a number of potentially toxic substances such as arsenic, cadmium, chromium, copper, lead, mercury, zinc etc (Veenstra *et al.*, 2006). Other constituents are pathogenic viruses, bacteria, protozoa and helminths.

The organic constituents of reclaimed wastewater are natural organic matter (NOM), soluble microbial products (SMPs) and trace levels of synthetic organic compounds (SOCs) and disinfection by products (Amy and Drewes, 2006b). Other wastewater constituents include trace organics such as ethylenediaminetetraacetic acid (EDTA) and nitrosdimethylamine (NDMA) etc. The dissolved organic carbon (DOC) present in reclaimed wastewater is composed of easily biodegradable organic carbon, natural organic matter, soluble microbial products and anthropogenic compounds (Fox *et al.*, 2005).

2.1.3 Levels of wastewater treatment

Physical, chemical and biological methods are used to remove contaminants from wastewater. In order to achieve the desired effluent quality, the wastewater is treated

through a number levels classified as preliminary, primary, advanced primary, secondary, secondary with nutrient removal, tertiary and advanced treatment (Brdjanovic, 2006). The levels of wastewater treatment are described in Table 2.1 and classification of treatment processes in Table 2.2.

Table 2.1 Levels of wastewater treatment (Source: Brdjanovic, 2006)

Treatment level	Description
Preliminary	Removal of wastewater constituents such as rags, sticks, floatables, grit and grease.
Primary	Removal of portion of suspended solids and organic matter from wastewater
Advanced primary	Enhanced removal of suspended solids and organic matter from the wastewater. Typically accomplished by chemical addition or filtration.
Secondary	Removal of biodegradable organic matter (in solution or suspension) and suspended solids.
Secondary with nutrient removal	Removal of biodegradable organics, suspended solids, and nutrients (nitrogen, phosphorus, or both phosphorus and nitrogen)
Tertiary	Removal of residual suspended solids (after secondary treatment), usually by granular medium filtration or micro screens. Disinfection is also typically part of tertiary treatment. Nutrient removal is often included in this definition.
Advanced	Removal of dissolved and suspended materials remaining after normal biological treatment when required for various water reuse applications.

Table 2.2 Classification of wastewater treatment processes (Source: Brdjanovic, 2006)

Primary	Secondary	Tertiary	Advanced
<ul style="list-style-type: none"> • Screening • Grit removal • Sedimentation • Comminution • Flotation • Flow equalization • pH correction • Imhoff tank 	<ul style="list-style-type: none"> • Activated sludge • Extended aeration • Aerated lagoon • Trickling filter • Rotating bio-disc • Anaerobic reactors • Stabilization ponds • Constructed wetlands • Aquaculture 	<ul style="list-style-type: none"> • Nitrification • Denitrification • Chemical precipitation • Disinfection • Filtration • P removal • Constructed wetlands 	<ul style="list-style-type: none"> • Chemical treatment • Reverse osmosis • Electrodialysis • Carbon adsorption • Ion exchange • Hyperfiltration • Oxidation • Detoxification

2.2 Soil aquifer treatment (SAT) system for wastewater reclamation

2.2.1 Need for wastewater reuse

The present global population of about six billion is projected to almost double in the second half of this century, a bigger increase will be in third world countries. Fresh water resources alone can not meet the growing water demand and therefore wastewater is an alternative resource to augment water supply. Increase in water demand due to population

growth may lead to excessive exploitation of groundwater to meet the demand. This implies long term sustainability of groundwater is threatened by aquifer depletion due to groundwater withdrawals in excess of groundwater recharge (Bouwer, 2000).

Natural replenishment of groundwater occurs very slow therefore artificial recharge with reclaimed wastewater is an alternative to increase the rate of replenishment of groundwater in aquifers. Artificial groundwater recharge using wastewater effluent accomplished through infiltration via spreading basin or direct injection augment the water supply (Eusuff and Lansey, 2004). SAT technology was recognized nearly 40 years ago as having potential for augmenting natural recharge, replenishing overdrafted aquifer and storing water during surplus periods for future use (Eusuff and Lansey, 2004). SAT can be considered as sustainable wastewater treatment technology for indirect potable reuse. Advanced technologies have high capital and operation costs, are complex to operate and generally are not well suited for developing countries (Westerhoff and Pinney, 2000). The treated wastewater during SAT is stored in aquifers and then recovered for reuse.

The recovered water from aquifers may be used to augment water supply through indirect potable reuse. Indirect potable reuse of recovered water in agriculture helps to maintain environmental quality and provides sustainable agriculture while preserving scarce water resources. Also using nutrients available in wastewater may diminish the fertilization costs (Haruvy, 1998). The public confidence is also increased when reclaimed wastewater is put back into the natural systems such as streams and aquifer before recovery for reuse. The reason for this is that natural systems are generally robust with respect to the removal of human pathogens, the dominant concern to human health (Dillon *et al.*, 2006).

2.2.2 Soil aquifer treatment methods

SAT for groundwater recharge using wastewater effluent is accomplished through infiltration via spreading wastewater on basin, vadose zone injection well and direct injection methods (Eusuff and Lansey, 2004) A widely used recharge method is rapid infiltration through spreading recharge basins; direct injection of reclaimed water is used when land is not available (Fox *et al.*, 2005). Direct injection is also used where aquifers are confined. Groundwater recharge can be by means of trenches where land area is limited (Bouwer, 2002).

The advantages of groundwater recharge by surface spreading include: (a) Groundwater supply may be replenished in the vicinity of metropolitan and agricultural areas where groundwater over-drafting is severe and (b) Surface spreading provide added benefits of the treatment effect of soils and transporting facilities of aquifers (Asano and Cotruvo, 2004). The disadvantages include: (a) Big land requirement and (b) Clogging on the infiltration interface caused by biological and physical processes. Chemical process caused by algae photosynthesis change the pH in soil leading to precipitation of carbonate, gypsum, phosphorus and other chemicals in the soil cause clogging below the

infiltration interface (Bouwer, 2002).

The advantages of direct injection include: (a) Small land requirement. (b) Confined aquifer can be recharged. The disadvantages include (a) High wastewater quality pretreatment requirement compared to surface spreading method making SAT system indirectly expensive. (b) It requires frequent backwashing of the clogging layer which requires a dedicated pump in the well making the system expensive. For example 15 minutes of pumping once, twice or thrice per day is needed to prevent serious clogging (Bouwer, 2002).

2.2.2 Site selection and land requirements

Site selection for SAT system involves investigation of depths to groundwater, redox conditions, soil characteristics, groundwater flow pattern (Fox *et al.*, 2001b). Proximity to conveyance channel and/or wastewater reclamation facilities is also a practical factor to be considered when selecting a site for SAT (NCSWS, 2001). However, to design a system for artificial recharge infiltration rates of the soil must be determined and the unsaturated zone between the land surface and the aquifer must be checked for adequate permeability and absence of polluted areas (Bouwer, 2002).

The best surface soils for SAT systems are in the fine sand, loamy sand, and sandy loam range. Materials deeper in the vadose zone should be granular and preferably coarser than the surface soils (Pescod, 1992). The land requirement depends on the quantity of reclaimed wastewater to be treated, type of soil and method of groundwater artificial recharge. Recharge via shallow basins requires big land than recharge via direct injection to groundwater aquifers. Permeable soils with high infiltration rates minimize land requirements (Bouwer, 2002).

2.2.3 Pretreatment requirement

Pretreatment requirements for groundwater recharge vary considerably depending upon the purpose of groundwater recharge, sources of reclaimed wastewater, recharge methods, location and public acceptance (Asano and Cotruvo, 2004). Artificial recharge by method of spreading reclaimed wastewater in shallow basins requires permeable surface soils. During soil aquifer treatment clogging layer that develops at the infiltration interface results in reduction of infiltration rates. Clogging may be caused by physical, chemical, and biological processes. According to Bouwer (2002) pretreatment to remove suspended organic and inorganic solids is needed to avoid clogging on the infiltrating surface.

The main constituent that must be removed from raw sewage before it is applied to a SAT system is suspended solids. Reductions in BOD and bacteria are also desirable, but less essential. However a higher BOD content would result in somewhat lower hydraulic loading rates for the SAT system and would require more frequent basin cleaning (Pescod, 1992). Pretreatment processes that leave high algae concentration in recharge

water should be avoided since algae can severely clog the SAT system (Asano and Cotruvo, 2004). Also, algae, being photosynthetic, remove dissolved carbon dioxide from the water, which increases the pH of the water. At high algal concentrations, this can cause the pH to rise to 9 or 10 which, in turn, causes precipitation of calcium carbonate. This cements the soil surface and results in further soil clogging and reduction of infiltration rates (Pescod, 1992). The pretreatment of reclaimed wastewater takes place in wastewater treatment plants. Figure 2.1 shows the vadose zone and the clogging layer that covers the infiltration interface.

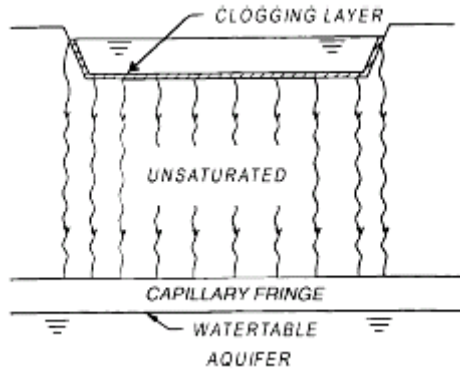


Figure 2.1. Section showing infiltration basin with clogging layer, unsaturated flow to the aquifer and capillary fringe above water table (Source: Bouwer, 2002)

2.2.4 Methods of operation

The operation of groundwater recharge facilities during SAT involves the wetting and drying cycles (Figure 2.2) this is particularly to avoid clogging of the system at the same time transforming nitrogen species (Amy and Drewes, 2006b). At the basin-soil interface, combined effect of sedimentation, filtration, aeration, microbial growth lead to the formation of biologically active zone that may become impermeable (Fox *et al.*, 2005).

The wetting and drying cycles which takes several days helps to prevent clogging and therefore basin soil interface do not become impermeable. When the recharge basin dries the clogging layer dry, decompose, shrink, cracks, and curl up restoring its permeability (Bouwer, 2002). During the drying cycle re-aeration takes place and the redox potential increases. Wetting and drying cycles typically vary from 8 hours dry-16 hours flooding to 2 weeks dry-2 weeks flooding, (Pescod, 1992). SAT systems should have a number of basins so that some basins can be flooded while others are drying.

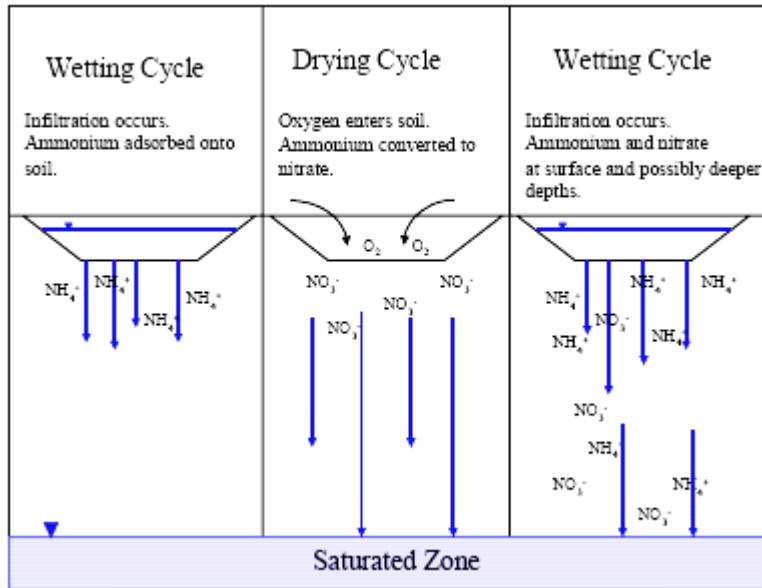


Figure 2.2 Infiltration process and nitrogen species in recharge basin including operations in wetting and drying cycles (Source: Fox et al., 2001b).

2.2.5 Challenges to using wastewater for groundwater recharge

Using reclaimed municipal wastewater for artificial recharge of groundwater presents a wide spectrum of technical and health challenges. One of the major issue associated with SAT leading to potable and non potable reuse of reclaimed wastewater is the presence of potentially harmful organic compounds, trace elements and pathogens that eventually may be consumed by public (Asano and Cotruvo, 2004). Incidental or unplanned indirect potable reuse of polluted water may expose people to health risks. Non potable uses such as irrigation have less potential for human exposure to hazardous agents and the risks are therefore significantly lower (Veenstra *et al.*, 2006).

Pathogenic organisms and trace organic compounds are by far a predominant concern to public health, it is important to design multiple barriers systems to assure continuous production of safe water. Therefore, SAT process should be designed and managed to avoid encroachment into the native groundwater (Asano and Cotruvo, 2004). However, the infiltration of reclaimed wastewater via soil percolation generally removes microorganisms such bacteria, viruses and therefore serves as a protection against direct health effects (Ernst *et al.*, 2000).

2.3 Factors affecting efficiency of SAT system

2.3.1 Influent wastewater quality

Soil aquifer treatment relies on natural processes to polish treated wastewater. The quality of wastewater prior to application to SAT system has an impact on SAT effluent quality. Near the soil water surface, biological activity with wastewater with high total oxygen demand will utilize all the dissolved oxygen leading to anoxic conditions in the saturated zone (NCSWS, 2001). Anoxic conditions are important for heterotrophic denitrification, typically a C:N ratio greater than 2 is needed for optimal heterotrophic denitrification (Fox *et al.*, 2001b). When most of the organic carbon is consumed at the soil water surface the remaining organic carbon is less biodegradable reducing the removal efficiency of SAT system.

Higher nitrogen removal is likely to be achieved using primary effluents as compared secondary effluents. This is attributed to the availability of the carbon source for denitrification due to high organic concentration in primary effluents (Katukiza, 2006). If the nitrogen in the wastewater is already mostly in the nitrate form and the water quite stabilized, organic carbon (as primary effluent, for example) may have to be added to the wastewater prior to SAT to achieve sufficient denitrification. Details of the effect of wastewater quality on removal of different contaminants during SAT are discussed in section 2.4.

2.3.2 Aerobic, anoxic and anaerobic conditions

The operation of SAT systems with wet/dry cycles is a common operating strategy. The primary purpose of wet/dry cycle operation is to control development of clogging layers at the infiltration interface and maintain high infiltration rates, and in some cases disrupt insect life cycles. The drying cycle allows for dessication of the clogging layer and the recovery of infiltration rates during the next wetting cycle (NCSWS, 2001). Wet/dry cycles control redox conditions in the subsurface. Aerobic condition during dry cycle allows oxygen to penetrate to greater depths as drying time is increased. Wet/dry cycle have important effect on nitrogen transformation. Increasing wet cycle increase the depth at which ammonia is adsorbed while increasing dry cycle times increase the depth at which ammonia is nitrified (NCSWS, 2001).

Dissolved oxygen decreases as wastewater percolates through the vadose zone and redox potential decreases, anoxic condition develops and Nitrate become the next electron acceptor (Fox *et al.*, 2001b). With sufficient organic carbon Nitrate is converted to nitrogen gas. According to Fox *et al.*(2001b) anaerobic oxidation of ammonia (ANAMMOX) exist in SAT systems due to the fact that the many systems are highly efficient in denitrifying ammonia without having sufficient C:N ratio required for heterotrophic denitrification. Most SAT system has C:N ration of 2 or less. Depending on oxidation state C:N ratio of 4 and 8 would result in 80% nitrogen removal efficiency under heterotrophic denitrification. However, the true mechanisms of ANAMMOX are

still being researched. The removal efficiency of kjeldahl nitrogen and ammonia has been found to reduce after few years of SAT operation. This has been attributed to the formation of anaerobic conditions in the SAT system preventing ammonia to nitrate conversion since growth of nitrifiers requires oxygen (Katukiza, 2006).

2.3.3 Hydraulic parameters

The main hydraulic parameters that affect SAT processes include infiltration rates, permeability, retention time and groundwater hydrogeology.

i. Infiltration rates

Infiltration rate vary inversely with water viscosity this implies temperature affect infiltration rate (Bouwer, 2002). In recharge basins decrease in infiltration rates is caused by physical and biological clogging. Infiltration rate has direct impact on retention time and hence DOC removal (Katukiza, 2006). On the other hand groundwater table also affects the infiltration rates. When the water table is more than about 1.0 m below the bottom of the recharge basin the infiltration rates are not affected by the changing water levels. If water table rises to less than 1.0 m below the bottom of the recharge basin the infiltration rates decreases linearly with decreasing depth (Bouwer, 2002). Typical infiltration rates range from 0.5 to 3m per day during flooding (Bouwer, 2000).

Seasonal effects affects infiltration rate, infiltration rate in winter are often less than in summer due to cooler water with higher viscosity. Infiltration rates are site specific and are best evaluated on pilot basins or on actual systems. Schedule of flooding for optimum infiltration rates are developed by trial and error (Bouwer, 2002). The infiltration rate can be calculated by using Green-and-Ampt equation for infiltration into a flooded soil shown below;

$$Vi = K \frac{H_w + L_f - h_{we}}{L_f} \quad 2.1$$

Where, Vi = the infiltration rate (m/day)

K = the hydraulic conductivity of wetted zone (m/day)

H_w = the water depth above soil (m)

L_f = the depth of wetting front (m)

h_{we} = the capillary suction or negative pressure (m)

These symbols are shown on Figure 2.3. Values for h_{we} on different type of sand are shown in brackets include; coarse sands (-5 cm), medium sands (-10 cm), fine sands (-15 cm), loamy sands-sandy loams (-25 cm), loams (-35 cm), structured clays (-35 cm) and dispersed clays (-100 cm).

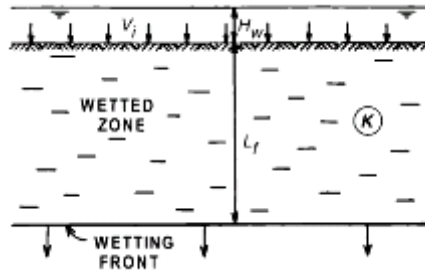


Figure 2.3 Section showing geometry and symbols for Green and Ampt equation (Source: Bouwer, 2002)

Equation 1 does not include the effect of clogging layer on infiltration, when considered infiltration rate can be calculated as shown below;

$$V_i = K_c \frac{H_w - h_{ae}}{L_c} \quad 2.2$$

Where;

V_i = infiltration rate (m/day)

K_c = hydraulic conductivity of the clogging layer (m/day)

H_w = the water depth above the clogging layer (m)

h_{ae} = the air entry value of the vadose zone soil estimated as $2 h_{we}$ (m)

L_c = thickness of the clogging layer (m)

ii. Permeability

According to Bouwer (2002) SAT systems require permeable soils to get water into the ground and to the aquifer. Permeability depends on types of soil and porosity. During SAT clogging caused by biological processes and suspended solids at the infiltration interface reduces the permeability of soil leading to declined infiltration rates. Permeability affects percolation through the vadose zone and the treatment processes in SAT systems (Katukiza, 2006). Table 2.3 shows typical permeability values for different types of soil.

Table 2.3 Typical permeability values of the various soils (Source: Bouwer, 2002)

Soil	Permeability (m/day)
Clay soils	<0.1
Loams	0.2
Sandy loams	0.3
Loamy sands	0.5
Fine sands	1.0
Medium sands	5.0
Coarse sands	>10.0

iii. Retention time

Microbial activity in degradation of organic matter requires sufficient time for growth of microbial population under optimum conditions. Nitrification and denitrification processes will not be complete within a short time. Removal of refractory organics usually requires long periods (Katukiza, 2006). The incomplete nitrification in practice occurs if operation schedule of a recharge basin is more condensed which leads to incomplete ammonia conversion to nitrate. The condensed schedule is when higher volumes of wastewater are recharged in a shorter wetting period followed by shorter drying period (Fox *et al.*, 2001b). Wetting and drying cycles typically vary from 8 hours dry-16 hours flooding to 2 weeks dry-2 weeks flooding (Pescod, 1992).

iv. Groundwater table

Groundwater provides further treatment of reclaimed wastewater by dilution as groundwater is transported in the aquifer (Amy and Drewes, 2006b). However, the water table may affect the biochemical processes involved in conversion of ammonia. During infiltration periods dissolved oxygen concentrations can be < 1mg/L, when infiltration is stopped the upper soil layer is re-aerated resulting in cyclic aerobic-anoxic conditions in the vadose zone (Fox *et al.*, 2005). Re-aeration process occurs during the drying cycle at the same time ammonia is converted to nitrate (Amy and Drewes, 2006b). This implies that when the water table is about the same as water surface of recharge basin or the infiltration interface the ammonia conversion to nitrate will be affected since there will be no drying cycle.

2.3.4 Site characteristics

Site characteristics are function of geology and hydrogeology. Soil properties can affect infiltration rates, bacterial attachment, re-aeration rates and adsorption. Soils with high hydraulic conductivities provide high infiltration rates during the beginning of wetting cycles during SAT and infiltration rates decrease as clogging layers develop (NCSWS, 2001). In addition surface infiltration system requires transmissive aquifers to get lateral flow away from the infiltration system without excessive groundwater mounding (Bouwer, 2002).

Conditions are favorable for adsorption and cation exchange on clay particles in the vadose zone (Martin and Koerner, 1984). The adsorption of ammonia during SAT is a function of cation exchange capacity and effluent cation composition. The large ratio of soil to water used during SAT makes moderate cation exchange capacities sufficient to remove ammonia by adsorption (NCSWS, 2001). Other contaminants whose removal largely depends on soil characteristics include virus (Quanrud *et al.*, 2003b) and heavy metals (Lin *et al.*, 2004). However, adsorption is not a major removal mechanism of organic carbon during SAT but biodegradation (Fox *et al.*, 2005). Therefore favorable conditions for biodegradation are needed for a site where SAT systems are to achieve required effluent quality from the system. Unsaturated condition is required to allow oxygen for microorganisms decomposing organic carbon and venting of gases as well as vaporization of volatile fractions (Martin and Koerner, 1984).

2.4 Effects on wastewater constituents during SAT

2.4.1 Introduction

SAT technology makes use of soil to treat the reclaimed wastewater, the treatment process occurs through infiltration, soil percolation, and transport through the groundwater aquifer (Figure 2.4). During the groundwater recharge through the vadose zone and transport through the groundwater aquifer, water quality improvements occur that are collectively described as Soil aquifer treatment (Eusuff and Lansey, 2004). Filtration, Sorption and biodegradation processes in the soil are mechanisms that can reduce or remove microbial and other contaminants in wastewater (Powelson *et al.*, 1993). Table 2.4 shows the comparison of SAT zones in terms of what is happening in the particular zone. Table 2.5 shows the removal of some contaminants from wastewater during SAT at operational field sites.

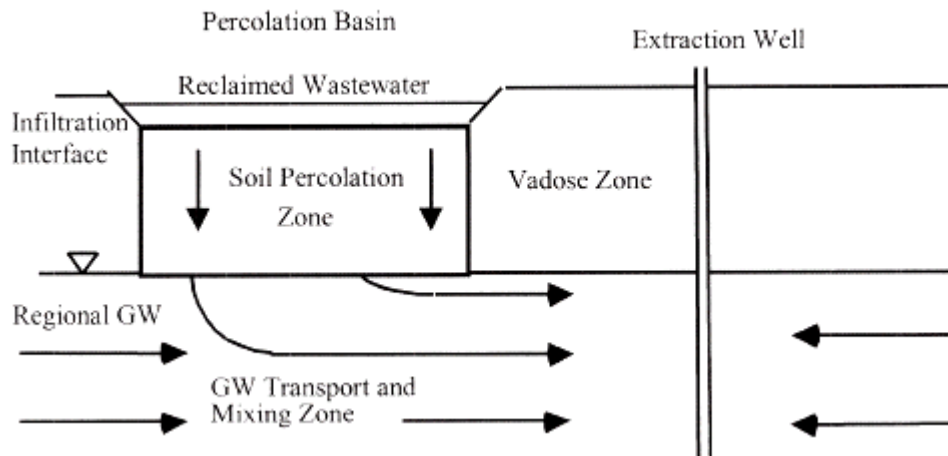


Figure 2.4 Schematic of SAT system (Source: Fox et al., 2005)

Table 2.4 Comparison of typical SAT zones (Source: Amy and Drewes, 2006b)

Process/parameter	Infiltration interface	Soil percolation	Groundwater transport
Treatment mechanisms	Filtration, biodegradation	Biodegradation, adsorption	Biodegradation, adsorption, dilution
Transport	Saturated	Unsaturated	saturated
Residence time	Minutes	Hours to days	Months to years
Travel distance	Inches/centimeters	10-100 ft/3-30 m	Variable
Mixing	No	No	Yes
Oxygen supply	Recharge water	Unsaturated zone	Regional groundwater
Biodegradable carbon availability	Excess	Excess/limiting	limiting
Redox conditions	Aerobic	Aerobic to facultative (denitrifying)	Aerobic to anaerobic

Table 2.5 Removal of different contaminants during SAT at some field sites/studies in India and USA

Field site/ Laboratory	Influent type and quality	Contaminant	Influent quality	Removal efficiency	Sampling soil depth	Recovery/ monitoring well location	Type of study	Source
Sweetwater, Arizona (USA)	Secondary + chlorination	NH ₄ -N	19 mg/L	98%	10 feet	Adjacent to recharge basin	Field study of existing groundwater recharge system	Amy and Drewes (2006b)
		NO ₂ -N	2 mg/L	-300%				
		NO ₃ -N	2 mg/L	-500%				
		DOC	13.31 mg/L	60%				
		EDTA	25.5 µg/L	-26%				
		NTA	4.4µg/L	64%				
		APECs	µg/L	33%				
Arizona state University (USA)	Secondary	DOC	17 mg/L	70%	-	-	Batch experiments	Westerhoff and Pinney (2000)
		DOC	17 mg/L	73%	90 cm	-	Soil column experiments	
Ahmedabad (India)	Primary	BOD	93 mg/L	90%	25 m	Centre of recharge basin	Pilot SAT system	Nema <i>et al.</i> (2001)
		COD	230 mg/L	90%				
		NH ₃ -N	42 mg/L	50%				
		PO ₄ -P	3.5 mg/L	90%				
		Total coliform	2 x 10 ⁷ MPN/100 mL	4-5 logs				
		Faecal coliform	3 x 10 ⁶ MPN/100 mL	4-5 logs				
		Faecal streptococci	2.8 x 10 ⁶ MPN/100 mL	4-5 logs				

- Sign means a contaminant is produced or released from the soil

2.4.2 Suspended solids and trace elements

After appropriate pretreatment in wastewater treatment plants, the suspended solids in effluent are usually relatively fine particles and in organic form. The suspended solids during SAT are removed by filtration and sedimentation. Suspended solids are essentially completely removed from the sewage effluent after about 1m of percolation through the vadose zone (Pescod, 1992). Sewage effluent contains a wide spectrum of other chemicals at low concentrations, these include heavy metals. Metals are significantly retained in most soils, the removal of heavy metal is by adsorption onto soils (Lin *et al.*, 2004).

2.4.3 Organic matter

Organic matter is the mixture of organic compounds divided into dissolved organic carbon (DOC) and particulate organic carbon (POC), based on filtration through a 0.45 µm filter. Generally DOC is of greater abundance accounting for 90% of the total organic carbon of most waters (Aiken, 2002). During SAT wastewater containing effluent organic matter (EFOM) from various sources (Figure 2.5) is introduced into the groundwater recharge basins for treatment using the soil. EFOM consists of NOM, SMPs, with trace levels of DBPs and SOCs (Amy and Drewes, 2006b). Adsorption and biodegradation are considered to be the dominant removal processes for EFOM (Rauch-Williams and Drewes, 2006). Aerobic, anoxic and anaerobic conditions promote biodegradation of organic carbon under different electron acceptors in SAT systems. Dissolved oxygen decreases as wastewater percolates through the vadose zone and redox potential decreases, Nitrate become the next electron acceptor followed by iron or manganese (Fox *et al.*, 2001b). Under aerobic conditions, breakdown is generally faster and more complete than under anaerobic conditions (Pescod, 1992).

Other treatment mechanisms are dilution, dispersion and filtration. According to Fox *et al.* (2005) the major removal process of organic matter is biodegradation. In general under SAT conditions, DOC and THMs are decreased, but TOX are less attenuated. Most of the removal occur near the surface of spreading basin during groundwater recharge with reclaimed wastewater (Rostad, 2002). During SAT a high removal efficiency (>90%) can be achieved for organic constituents (Cuyk *et al.*, 2001). A pilot study carried out at Ahmedabad in India revealed that about 90% BOD and COD removal was achieved when primary effluent was applied to SAT systems (Nema *et al.*, 2001). At Sweetwater recharge facility in USA >90% DOC removal was achieved by applying chlorinated secondary effluent (Quanrud *et al.*, 2003c) DOC removal is independent of the DOC concentrations in the applied effluents but dependent on concentrations of easily biodegradable carbon remaining after pre-treatment (NCSWS, 2001).

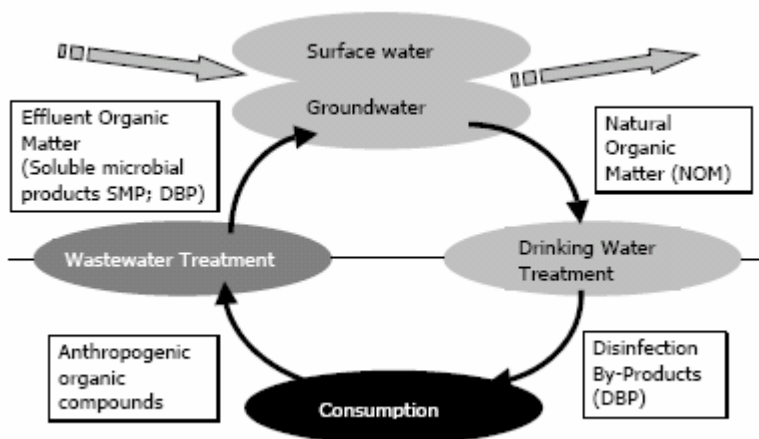


Figure 2.5 Sources of organic compounds for indirect potable reuse systems (Source: Fox et al., 2001b)

2.4.4 Trace organic compounds

Trace organics are potentially harmful compounds. Trace organic compounds that are introduced to the environment via effluents include ethylenediaminetetraacetic (EDTA), nitrilotriacetic acid (NTA), naphthalenedecarboxylic acid (NDC), alkylphenolpolyethoxycarboxylates (APEC). The compounds are representative of many anthropogenic contaminants in wastewater and most abundant in wastewater effluents (Fox *et al.*, 2001b). EDTA and NDC are commonly used as complexing agents in laundry detergents and industrial cleaning agents and in various other applications like agriculture fertilizer. The origin of NDC is unknown. APEC compounds are biological metabolites of alkylphenol polyethoxylates (APEs) a class widely used as nonionic surfactants (NCSWS, 2001).

Three phenomena of importance in the transport and fate of organic micro pollutants in SAT systems are biodegradation, sorption and volatilization (Bouwer *et al.*, 1981). The three processes are useful in attenuation for trace organic compound. According to Bouwer *et al.* (1981) biodegradation destroy organic compound, volatile trace organic compound may be removed by mass transfer from liquid to the gaseous phase and then to the atmosphere. Sorption processes retard the movement of trace organic compounds in the soil system.

In investigating the removal of trace organics from secondary effluents at Tucson recharge basins in United States of America (USA), it was found that after approximately four weeks of travel through the unsaturated soil the removal efficiencies of EDTA, NTA, NDC and APEC were 86%, 98%, 94% and 99% respectively (NCSWS, 2001). However the concentration of trace organics may fluctuate in the vadose zone during SAT (Figure 2.6). In Mesa North waste recharge basins in USA the removal efficiency for the same contaminants were 71%,100%, 91% and 98% fro tertiary effluents (Fox *et al.*, 2001b). Figure 2.7 shows the behavior of some trace organics and surrogates. Generally, the removal efficiency increases with travel distance.

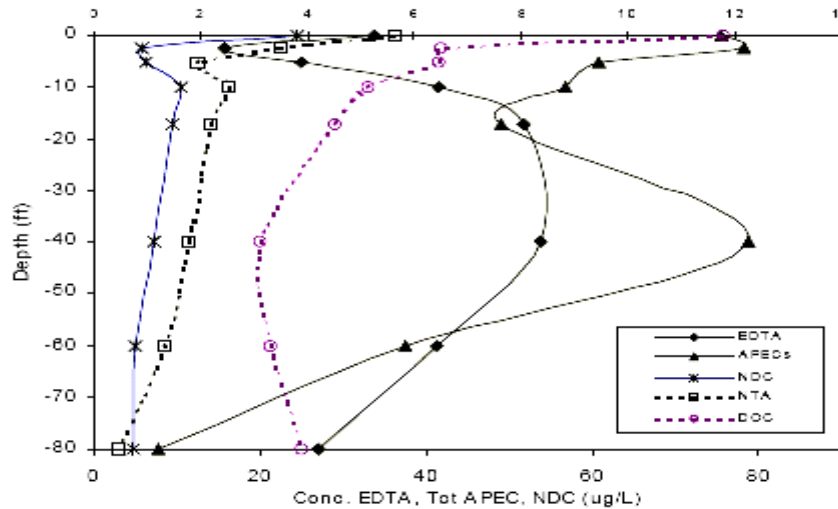


Figure 2.6 Trace organic concentration vs. depth for one recharge basin in Tucson, Arizona in USA (Source: Fox et al., 2001b)

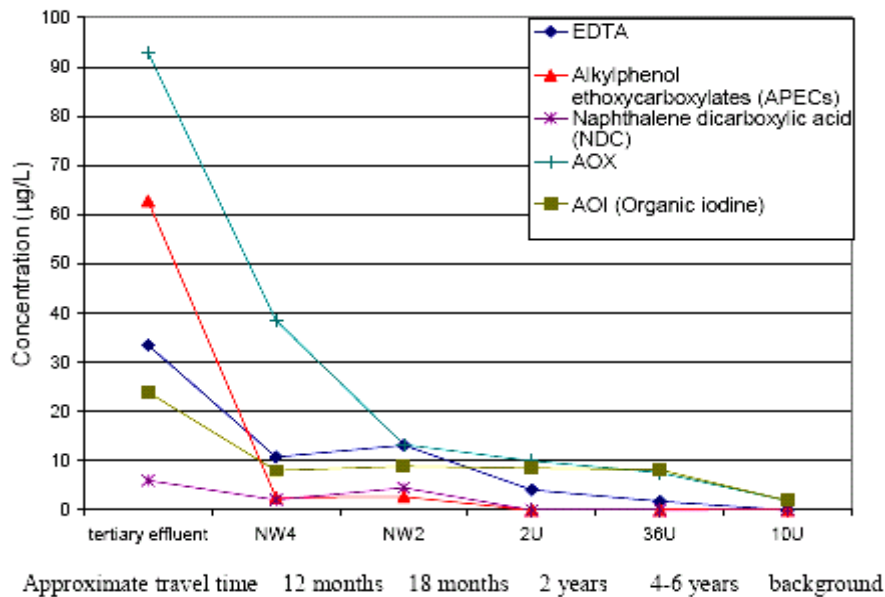


Figure 2.7 Behaviour of some trace organic compounds and surrogates during SAT at the Northwest Water Reclamation plant Mesa, Arizona (Source: NCSWS, 2001)

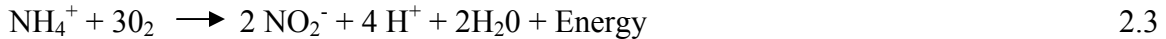
2.4.5 Nitrogen species

Nitrogen is very important in wastewater management because nitrogen has many effects in environment like eutrophication, oxygen depletion and toxicity. Ammonia is extremely toxic to fish and other aquatic organism, it is also oxygen consuming compound which can deplete dissolved oxygen in aquatic environment. Nitrogen species present in wastewater usually include various form of organic and inorganic nitrogen (ammonium,

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nitrite and nitrate); raw sewage has considerable organic nitrogen (Brdjanovic, 2006). Significant nitrification and simultaneously denitrification can occur during SAT, providing removal of nitrogen from the system (Pescod, 1992). Nitrogen species are removed by bacteria under anoxic and aerobic conditions during SAT. In ammonification, microorganisms decompose organic nitrogen to produce ammonia. Nitrification and denitrification processes are shown in equations below;

Conversion of ammonia to nitrite by *Nitrosomonas*;



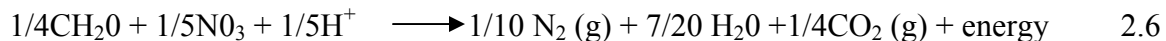
Conversion of Nitrite to Nitrate by *Nitrobacter*;



The overall conversion of ammonia to nitrate;



Conversion of Nitrate to Nitrogen gas (Heterotrophic denitrification);
Microorganisms involved here are heterotrophs



Necessary condition for nitrification is predominant oxic condition and pH should not exceed 10 (Rice and Bouwer, 1984). The necessary condition for denitrification include absence or near absence of molecular oxygen and adequate supply of electron donors and a capable bacteria population (Miller *et al.*, 2006).

Nitrification process reduces the ammonia concentration by converting it to nitrate during the drying cycle of the recharge basin (Figure 2.2). Due to net positive charge of ammonium ion it is adsorbed at the upper part of the vadose zone during the wetting cycle. During the drying cycle as soil dries air /or oxygen enters the soil, oxidation of ammonia to nitrate by nitrifiers may occur in the vadose zone. During drying near atmospheric levels of oxygen (18%) can be reached to a depth of approximately 1.0 m (Yoo *et al.*, 2006). Figure 2.5 shows that ammonia is significantly removed at few feet below the recharge basin.

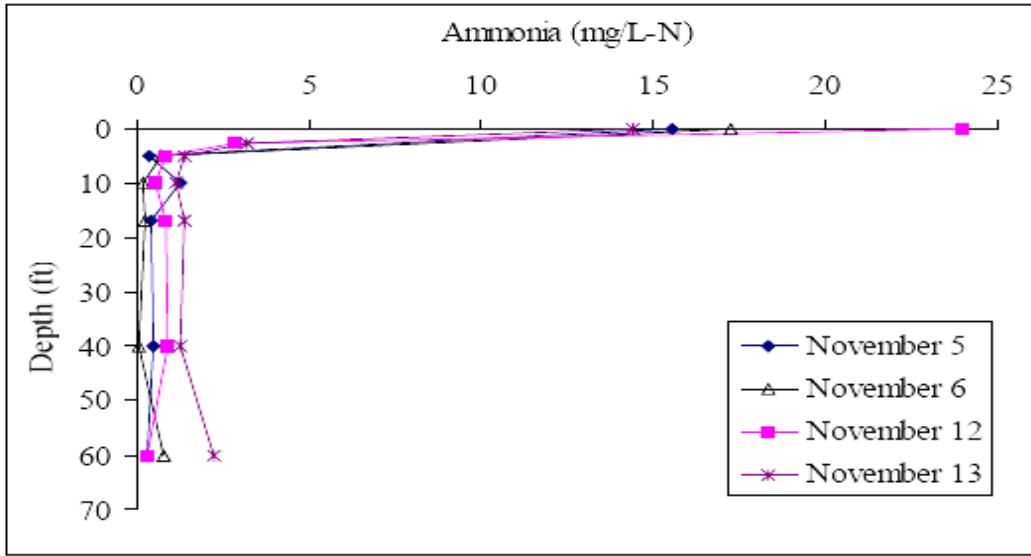


Figure 2.8 Removal of ammonia from secondary effluent during soil aquifer treatment (SAT) field site recharge basin in Tucson, Arizona in USA (Source: Fox et al., 2001b)

Once nitrate reaches deeper (Figure 2.8) into the anoxic zone, heterotrophic denitrification may convert nitrate into nitrogen gas in the presence of organic carbon as electron donor (Fox *et al.*, 2001b). C:N ratio influence nitrogen removal, C:N ratio greater than 3 is necessary to sustain high nitrogen removal efficiency (Fox *et al.*, 2001b). In field sites the removal efficiency of nitrogen is site specific, for example the Dan region recharge project in Israel reported nitrogen removal efficiency of 45% with C:N ratio 2:1 while the Tucson Sweetwater site in USA reported a removal efficiency 25-90% with C:N ratio less than 1:1 (Fox *et al.*, 2001b). According to Fox *et al.* (2001b) the Dan region recharge project has sufficient organic carbon to sustain heterotrophic denitrification. The high removal efficiency of nitrogen species may be attributed to anaerobic ammonium oxidation (ANAMMOX) at Tucson Sweetwater site. SAT operation schedule also have influence on removal of organic species (Rice and Bouwer, 1984). Ammonia conversion to Nitrate in porous media can be estimated as shown in the equation below;

$$\frac{C_1}{C_s} = \exp \left[\frac{ux}{2D} \left(1 - \sqrt{1 + \frac{4Dk_1}{u^2}} \right) \right] \quad 2.7$$

$$\frac{C_1}{C_2} = 1 - \frac{C_1}{C_s} \quad 2.8$$

Where,

C_1 = Influent concentration of $\text{NH}_4\text{-N}$ (mg/L)

C_2 = $\text{NO}_3\text{-N}$ concentration (mg/L)

u = Pore water velocity (cm/h)

x = Distance within the soil (cm)

D = Hydrodynamic dispersion coefficient (cm²/day)

k_1 = First order reaction rate for nitrification (h⁻¹)

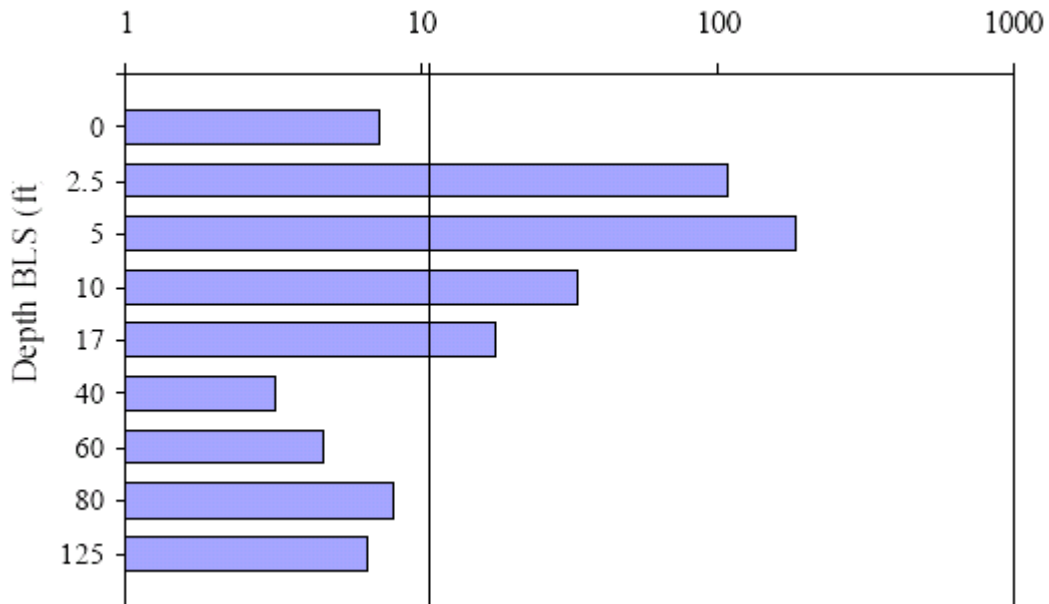


Figure 2.9 Nitrate concentration changes versus depth during SAT of secondary effluent in the filed site in tucson, arizona in USA (Source: Fox et al., 2001b)

2.4.6 Bacteria and viruses

One of the principal issues associated with indirect potable reuse are potentially harmful microorganism that pass through conventional and advanced water treatment systems (Drewes *et al.*, 2003). Microbial activity in the subsurface is mainly driven by the net decomposition of organic matter, which provides microorganisms with the energy, nutrients and electrons they need to synthesize biomass and sustain life functions (Hunter *et al.*, 1998).

The removal of virus is controlled by number of factors, most important factors are type of soil, type of virus, infiltration rate and the degree of soil saturation (Quanrud *et al.*, 2003b). However, virus are removed through inactivation and adsorption mechanism (Powelson *et al.*, 1993). Conditions are favorable for adsorption on the clay particles of the vadose zone (Martin and Koerner, 1984). Virus removal is more in unsaturated zone than saturated zone (Nema *et al.*, 2001).

Bacteria are removed by filtration, predation, adsorption and the occurrence of adverse conditions (Katukiza, 2006). Human bacteria and viruses immobilized in the soil do not reproduce, and eventually die. Most bacteria and viruses die in a few weeks to a few months, but much longer survival times have also been reported (Pescod, 1992). Powelson *et al.* (1993) on studying virus removal during SAT found that human enteric viruses have low adsorption to soil and survive longer in the environment (Powelson *et al.*, 1993). Also found that bacteria concentration does not always decline with depth probably due to preferential flow condition. The death of microbes can be a calculated

using microbial decay equation which is based on Chick's law;

$$\ln\left(\frac{C}{C_0}\right) = -kt \tag{2.9}$$

Where;

C = the number of viable microorganisms remaining in water (MPN/100mL or pfu/mL)

C_0 = Number of microorganisms in influent water (MPN/100ml or pfu/mL)

k = is an empirical constant descriptive of the microorganism, pH and type of disinfection used (for SAT physical disinfection) (h^{-1})

t = time (hours)

Example of application of equation 2.9; the following table shows the disinfection of poliomyelitis virus using filtration as a physical disinfectant. Determine Chick's constant and the time required to reduce the concentration of viable polio virus to 1/10,000 (4 log removal) of the original concentration. The change in concentration of microbes with respect to time is summarised in table 2.6

Solution;

Plot $-\ln(C/C_0)$ against time (t)

Determine the slope of the line, the slope which yields k value (Figure 2.10)

Table 2.6: Measured data for determination of k value (Source: SWBIC., 1998)

t (hours)	4	8	12
C/C_0	0.0769	0.00633	0.00050
$-\ln(C/C_0)$	2.57	5.06	7.60

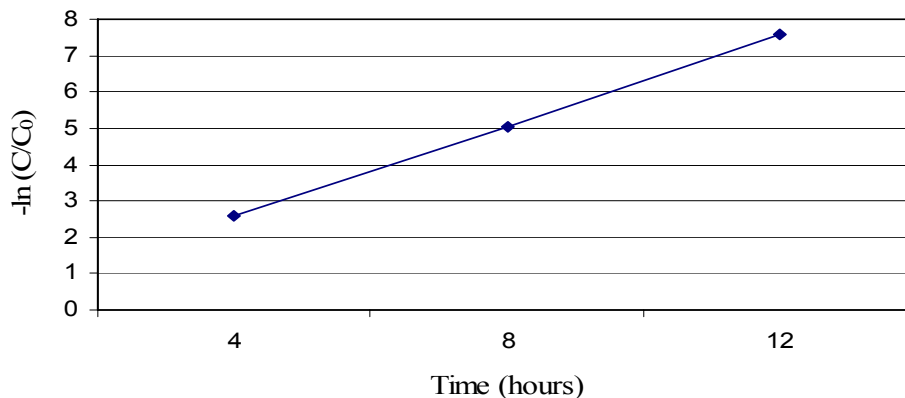


Figure 2.10 k value determination

The slope of the line in Figure 2.10 is 0.634/h

The time required for 10,000 fold reduction of microbe is

$$t = \frac{-\ln\left(\frac{C}{C_0}\right)}{k} = -\ln(1/10000)/0.634 \text{ h} = 15 \text{ hours} \quad 2.10$$

2.4.7 Phosphorus

The excessive content of phosphorus leads to extensive growth (eutrophication) of algae in surface waters. Eutrophication may increase significantly the cost of water treatment in surface water treatment plants (Rybicki, 1997). The main sources of phosphorus in municipal sewage are excreta and detergents. Raw sewage can contain 5 mg/l to 50 mg/l of phosphorus depending on diet and water use on local population (Pescod, 1992). The activated sludge treatment plants can reduce significantly the phosphorus concentration in wastewater. The basic configuration of activated sludge treatment plant consist of anaerobic and aerobic zone, phosphorus removal is through biological process in aerobic zone (Brdjanovic, 2006). The phosphorus removal during SAT is through adsorption to soil as reclaimed wastewater percolates the soil and sediments (Lin and Banin, 2005; Lin and Banin, 2006; Viswanathan *et al.*, 1999). Other mechanisms include filtration and microbial uptake (Idolevitich and Michail, 1984). However, phosphorus adsorption is controlled by the interaction of redox potential, pH, native iron, calcium and aluminium minerals and the iron to P ratio (Rogers *et al.*, 2005). According to Idolevitich *et al.* (2003), the main removal process for phosphorus is chemical precipitation reaction with the calcium and magnesium ions present in the soil and adsorption. Furthermore, phosphorus is removed by adsorption onto iron and aluminum containing minerals and precipitation with these minerals (Reemtsma *et al.*, 2000).

2.5 Transfer of SAT technology to developing countries

2.5.1 Introduction

The previous sections have shown that SAT technology can remove many contaminants from wastewater effluents using different mechanisms under different redox conditions simultaneously recharging the aquifer. SAT systems have been used in augmenting water supply especially for indirect potable reuse in large scale in arid and semi arid regions of few developed countries which includes USA (Amy and Drewes, 2006b) and Israel (Haruvy, 1998). Reuse of treated wastewater has become an integral facet of water management in developed countries (Westerhoff and Pinney, 2000). As mentioned in section 2.2.1 it is estimated that most of the global population increase will take place in third world countries. According to Bouwer (2000) these countries already suffer from water, food and health problems. Application of SAT technologies in wastewater treatment in these countries would help to recharge the groundwater aquifers. The water can then be recovered for reuse for various purposes depending on SAT system effluent quality. However, this technology has to be transferred from different parts of the world to these developing countries.

There are many definitions of technology transfer. Technology transfer may be defined as a process whereby technology developed in one place is being diffused to another location (Haq, 1985) or technology transfer may be defined as the acquisition, development and utilization of technological knowledge by a country other than that in which this knowledge originated (Madu, 1989). Technology transfer to be successful should involve government agencies, private entities, and local community organisation. Regulatory and policy issues have to be addressed in transfer of technology (WMO and UNEP, 2000). However, for the technology to be accepted to the proposed country it has to be feasible and sustainable. The aspects of sustainability and feasibility for SAT technology and constraints are described in the following sections below;

2.5.2 Social aspects

Water and wastewater infrastructure and management are critical concerns for sustaining industrial growth and improving standards of living (Westerhoff and Pinney, 2000). Reuse of treated wastewater through groundwater recharge benefits people through the irrigation of crops, urban parks, sports fields etc, treatment of wastewater for local reuse may save or reduce the cost for discharge to receiving surface water bodies (Bouwer, 2000). As the cost for discharge is saved or reduced at the same time the environmental pollution is controlled, the community's burden of payment for wastewater is reduced and therefore their living standard may be improved. However, the acceptance importance of the people to SAT treated reclaimed water for potable or non-potable is equally important as it mainly dictates the success or failure of water reuse schemes.

2.5.3 Technical aspects

Advanced technologies have high capital and operation costs, are complex to operate (Westerhoff and Pinney, 2000). SAT technology may be very cheap where land is available. However, to implement SAT technology knowledge about depth to groundwater, redox conditions, groundwater flow pattern, hydraulic conductivity of different soils operation and maintenance is required (Bouwer, 2002; Fox *et al.*, 2001b; Pescod, 1992).

2.5.4 Health and environmental aspects

Pathogenic microorganisms are by far a predominant concern when wastewater is reused, trace chemicals should also be considered when wastewater is intended for reuse (Asano and Cotruvo, 2004). Reductions in biodegradable organics, suspended solids, phosphorus and nitrogen compounds, heavy metals, bacteria and may be achieved by rapid infiltration SAT systems (Powelson *et al.*, 1993). Reuse of wastewater reduces the amount of contaminants that could reach the water bodies and therefore the capacity of natural purification of receiving water bodies may be maintained (Gijzen, 2005). SAT technology makes reuse of wastewater possible simultaneously reducing environmental pollution. This is attributed to its ability to remove different contaminants and therefore it

is an attractive technology to be transferred for use in developing countries in arid and semi arid regions.

2.5.5 Economic and financial aspects

SAT technology offers a number of advantages including low initial cost, low operating cost, potential for revenue to offset operation costs and low energy requirements (Tomson *et al.*, 1981). Improved water quality, aquifer recharge and increased yield of crop irrigated using recovered water are some of the advantages of using SAT systems (Bouwer *et al.*, 1981). Indirect potable reuse in agriculture may provide employment to a majority of people who live in rural areas in many developing countries and therefore SAT technology is attractive to developing countries particularly those in arid and semi arid regions. Reuse of wastewater is also aimed at achieving sustainable urban water and nutrient management (Gijzen, 2005).

2.5.6 Institutional aspects

Advanced technologies require educated operators and generally are not suited for developing countries (Westerhoff and Pinney, 2000). SAT system like other wastewater treatment technologies it requires technical personnel to operate, however its operation is less complex as compared to some conventional technologies like activated sludge systems and membrane technologies. Rapid infiltration through spreading recharge basins of reclaimed is a widely used recharge method, the method is operated in wetting and drying cycles (Fox *et al.*, 2005).

SAT systems only require simple maintenances to control clogging at the infiltrating surface through the removal of clogging material at the end of drying period, reduction of nutrients and organic carbon through pretreatment processes helps in controlling the development of clogging layer (Bouwer, 2002). However, reuse of wastewater must be carefully planned and regulated to prevent adverse health effects (Bouwer, 2000). The regulator can be the government ministry, department or agency as it may be provided by the law of the country.

2.5.7 Constraints to transfer of SAT technology

The transfer of wastewater technology may be affected by a number of factors which includes limited financing, limited institution capabilities, jurisdiction complexity and need for community involvement (WMO and UNEP, 2000). SAT technology implementation although it is not as expensive as advanced technologies its implementation may be affected by these factors when implementation in developing countries is considered.

3.0 RESEARCH METHODOLOGY

3.1 Introduction

In order to achieve the goal and objective of this research, desk study method was adopted in which peer reviewed journals and other published and unpublished works relevant to soil aquifer treatment were collected, studied and useful data were extracted. This approach was selected since the guidelines have to be developed based on what the different SAT systems have achieved in contaminants removal to make them applicable. The resources for data include UNESCO-IHE lecture notes, UNESCO-IHE library, Technical University of Delft library and online publications. Data collected during desk study have been analysed in order to come up with guidelines for estimation of removal of different contaminants during SAT. After developing the guidelines the framework for transfer of SAT technology to developing country was developed. The framework includes the application of developed guidelines as well. This methodology is explained in detail below.

3.2 Desk study

Desk study (extensive literature review) was done in order to collect data relevant for this research from different SAT studies around the world. The data collected were analysed to find out how SAT systems perform in different parts of the world and under different operating conditions. The findings were used as a base to develop guidelines for estimation of removal of multiple contaminants during SAT.

The parameters which have been focused are:

- influent quality and effluent quality, that include;
 - i. Organic matter/ NOM (DOC)
 - ii. Trace organics
 - iii. microbes
 - iv. Nitrogen species
 - v. Phosphorus
- Contaminant removal efficiency
- Infiltration rates
- Residence/travel times.
- Redox conditions
- Travel distance
- Soil types/profile

Soil aquifer treatment of primary, secondary and tertiary effluents was studied. The SAT systems whose data are presented and discussed in this report include batch reactors, soil columns and SAT field site. Most of data in this report come from peer reviewed journals. Table 3.1 summarises the type/source of literature reviewed.

Table 3.1 Summary of type/source of literature reviewed

Literatures		Number of literatures
Peer reviewed journals	Name of journals	
	Environmental Monitoring Assessment	1
	Water Research	18
	Agricultural Water Management	1
	Hydrology Journal	1
	Water Science and Technology	15
	Water Science and Technology: Water Supply	3
	Journal of Environmental Engineering	5
	Water Resources Management	1
	Environmental Quality	1
	Engineering Management International	1
	Resources, Conservation and Recycling	1
	Journal of Hydrology	1
	Environmental Toxic Chemistry	1
	Water Pollution Control Federation	3
	Water, Air and Soil Pollution	1
	Chemosphere	1
	Long Range Planning	1
	Journal of Hazardous Material	1
	Desalination	1
	Journal of Water and Health	1
	Journal of Environmental Sciences	1
TOTAL		60
Lecture notes	Subject	
	Water quality	3
	Conversional wastewater Treatment	1
	Water reuse in agriculture	1
	Soil Aquifer treatment	1
TOTAL		6
Thesis	Research area	
MSc Thesis	Soil aquifer treatment	1
PhD Thesis	-	-
TOTAL		1
Report	Report type	
	Workshop proceeding on artificial recharge	2
Websites	Website hosts	
	FAO	1
	UNEP	1
	Springer	1
	UNIDO	1
	Royal Institute of technology (Sweden)	1
	Arizona State University (USA)	1
TOTAL		6
Books	Subject area	
	Soil aquifer treatment	2
TOTAL		2

3.3 Analysis of performance of SAT systems

The performance of SAT system in this research refers to its ability to remove contaminants expressed as removal efficiency in percentage. The first step in data analysis was to find out how different parameters influence the removal of contaminants. This was achieved through correlation analysis. No mathematical model or equation could be developed for prediction of water quality because of weak correlation of parameters to contaminant removal. The data analysis was done in steps as follows;

- Correlation analysis to find how different parameters influence the contaminants removal.
- Make scatter plots of contaminants removal efficiency.
- Grouping of data in bins according to scatter.
- Calculation of average contaminant removal efficiency with respect to travel distance and residence/travel time in each bin and the standard deviation.

The data were grouped in bins in order to set the travel distance and residence/travel time range to be used in guideline development. The bins were decided according to a) scatter of data whereby performance data which were closer were set as one group in one bin and where data were almost evenly distributed with travel distance or time, bins of equal travel distance or travel time were made b) Expert judgement whereby data that show a trend on removal of contaminant up to certain travel distance/time are grouped together in one bin while those which do not show trend are grouped in another bin. Different scales were selected for travel distance or travel time/residence time to illustrate properly the available data and because of the different travel distance or time scale used in the study of different parameters. SPSS package was used to prepare scatter plots. The standard deviation was calculated in order to find out how performances of SAT systems deviate from the mean. Where standard deviation was too big it implied that the performances of SAT systems within the bin are not comparable and chances for achieving average contaminant removal efficiency are less. Microsoft office excel was used for statistical analysis.

3.4 Guideline development

Guidelines for removal of contaminants were developed based on analysis of SAT performance data. Relevant assumptions were made where necessary. The assumptions include;

- Under normal operating condition the removal of contaminant increase with travel distance and residence/travel time
- Contaminant breakthrough is less likely
- Nitrate is produced up to certain distance then is removed
- Contaminants removed are derived from infiltrates from recharge source

Separate set of guidelines were developed to estimate the removal of different parameters from primary, secondary and tertiary effluents during soil aquifer treatment. These guidelines were then applied to typical wastewater effluents. Furthermore, the results of the use of these guidelines for DOC removal was also compared with results of a laboratory-scale study being conducted at UNESCO-IHE using secondary effluent.

3.5 Development of framework for transfer of technology

The framework for transfer of technology was developed by adopting some processes for transferring industrial technology as found from different literatures. It was done this way because industrial technology transfer issues may also apply to wastewater technology transfer. The issues related to industrial technology transfer that may apply to SAT technology transfer include pollution prevention, policy and research, socio-economic, political, technology promotion and implementation/investment. However literatures that describe transfer of either wastewater technology or SAT technology were not available.

4.0 RESULTS AND DISCUSSION

4.1 Introduction

The performance of field-scale and laboratory-scale SAT systems were analysed within the limits of scope of this study using the data obtained through a desk study. The coverage of SAT of different effluent types and contaminants in papers/studies is shown on Tables 4.1 and 4.2 respectively. Some studies only respond to travel distance others only travel time. Details of each field-scale/laboratory-scale SAT are summarised in Appendices A-Q. The field scale SAT facilities studied are located in USA, Israel, Germany, Kuwait, India and China. The laboratory-scale SAT studies which include batch and column experiments used different types of soil for SAT. The site SAT consisted of more than one infiltration basins with different soil profiles underlying the basins. The SAT systems received primary, secondary and tertiary effluents. In this report tertiary effluent refers to filtered effluents from rapid sand filters after conventional secondary treatment. The SAT site and experiments that received secondary effluents were from one of the following treatment facilities; oxidation ponds/aerated lagoon, trickling filters, activated sludge or ammonia stripping ponds. Based on SAT performance analysis, separate sets of guidelines for removal of contaminants from primary, secondary and tertiary effluents were developed followed by development of a framework for transfer of technology to developing countries. The guidelines are summarised on respective section describing their development. The general assumption in developing guideline is that under normal operating conditions the removal of the major contaminants studied namely; DOC, trace organics, ammonium, nitrate and microbes during SAT increases with travel distance and residence/travel time and that they are derived from infiltrates from recharge source only. Guideline's influent and effluent quality data of major pollutants that includes DOC, NH₄-N, NO₃-N and bacteria were presented in box and whiskers graph that shows 5, 25, 75 and 95 percentile and median for secondary SAT only.

Table 4.1 Summary of number of data sources used in this study for different effluents

No. of papers/studies on SAT of	Lab-scale SAT	Field-scale SAT	Total
Primary effluent	5	3	8
Secondary effluent	18	14	32
Tertiary effluent	6	10	16
Total	29	27	56

Table 4.2 Summary of number of data sources used in this study for different contaminants

No. of papers/studies on SAT of	Primary	Secondary	Tertiary	Total
DOC	3	21	13	37
NH ₄ /NO ₃	2	9	2	13
Phosphorus	3	6	2	11
Trace organics	1	7	4	12
Microbes	3	6	1	10
Total	12	49	22	83

4.2 Correlation analysis of DOC removal during SAT

The first step in data analysis was to study the correlation between different parameters during SAT to determine how these parameters are related. The correlation analysis for DOC removal during SAT was performed because organic carbon has an influence on removal of other contaminants, especially nitrogen species. The DOC attenuation occurred under different conditions and soil types. The correlation analysis was done for parameters which were considered to have an influence on DOC attenuation. The correlation matrixes for DOC removal during SAT of primary, secondary and tertiary effluents are shown on Tables 4.3, 4.4 and 4.5, respectively. Correlation coefficient between different parameters and DOC removal would approach ± 1 for a parameter that strongly influences DOC attenuation. In general, the results show that there is no strong correlation between DOC attenuation and the different parameters. This suggests that the removal of contaminants in SAT systems are case/site specific and may not be presented using one kinetic model. This also suggests that other process parameters such as pH, wastewater temperature, redox conditions and hydraulic loading rate which are not included in correlation matrix may have significant influence on DOC removal. In all three cases travel distance was the parameters which had the highest correlation coefficient with DOC removal efficiency. In case of correlation analysis of DOC removal during SAT of primary and secondary effluents travel distance and travel time had the highest correlation with DOC removal efficiency. Therefore, the data were further analysed to develop guidelines for removal of different contaminants with respect to travel distance or residence time. While the two most important factors are the travel distance and time also important are the redox and hydraulic loading rate.

Table 4.3 Correlation analysis of DOC removal during SAT of primary effluents

Number of data (n) = 8

	Influent DOC (mg/L)	Effluent DOC (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Travel time (day)	DOC Removal efficiency (%)
Influent DOC (mg/L)	1					
Effluent DOC (mg/L)	-	1				
Infiltration rate (m/day)	-	0	1			
Travel distance (m)	-	-0.32	0	1		
Residence time (day)	-	-0.32	0	1	1	
Removal efficiency (%)	-	-1.00	0	0.32	0.32	1

Table 4.4 Correlation analysis of DOC removal during SAT of secondary effluents

Number of data (n) = 58

	Influent DOC (mg/L)	Effluent DOC (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Travel time (day)	DOC Removal efficiency (%)
Influent DOC (mg/L)	1					
Effluent DOC (mg/L)	0.03	1				
Infiltration rate (m/day)	-0.23	0.43	1			
Travel distance (m)	0.30	-0.60	-0.15	1		
Residence time (day)	0.31	-0.62	-0.21	1.00	1	
DOC Removal efficiency (%)	0.58	-0.75	-0.54	0.65	0.67	1

Table 4.5 Correlation analysis of DOC removal during SAT of tertiary effluents

Number of data (n) = 18

	Influent DOC (mg/L)	effluent DOC (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	DOC Removal efficiency (%)
Influent DOC (mg/L)	1					
effluent DOC (mg/L)	0.60	1				
Infiltration rate (m/day)	-0.09	-0.74	1			
Travel distance (m)	-0.12	-0.47	0.18	1		
Residence time (day)	0.11	0.13	-0.40	0.46	1	
DOC Removal efficiency (%)	-0.11	-0.84	0.77	0.59	-0.05	1

4.3 Attenuation of contaminants from primary effluents and guidelines development

4.3.1 DOC removal and guidelines for estimation of water quality

Data presented and discussed in this section include DOC removal data from 4 SAT studies (one site SAT located in Mesa, Arizona USA, and three lab-scale SAT in batch experiments). The results of performance of SAT systems are plotted as shown in figures 4.1 and 4.2. One of batch SAT experiment with silica sand was operated under anoxic conditions for 15 days achieving 49% DOC removal. The remaining batch SAT experiment one with silica sand and another with poorly graded sand, were operated under oxic conditions for 15 days and 29 days respectively. The former and the later removed DOC at 58% and 29% respectively. These differences in batch SAT performance may be attributed to influent quality, which may be characterised by DOC components or operational conditions. The field-scale SAT removed DOC by 12-62% at a travel distance <1 m and travel time <1 day, Generally DOC removal in the vadose zone below the surface of recharge basin increased with travel time and distance. Rice and Bouwer (1984) found that SAT of primary effluent was capable of producing renovated water of equal or better quality than when using secondary effluent. The SAT site they studied demonstrated adequate capacity in handling higher organic carbon load. However, The primary effluent would have a higher BOD and suspended solids content than secondary effluent and this would result in somewhat lower hydraulic loading rates for the SAT system and would require more frequent basin cleaning (Pescod, 1992). The analysis of SAT data on DOC removal with respect to residence and travel time are summarized in Tables 4.6 and 4.7.

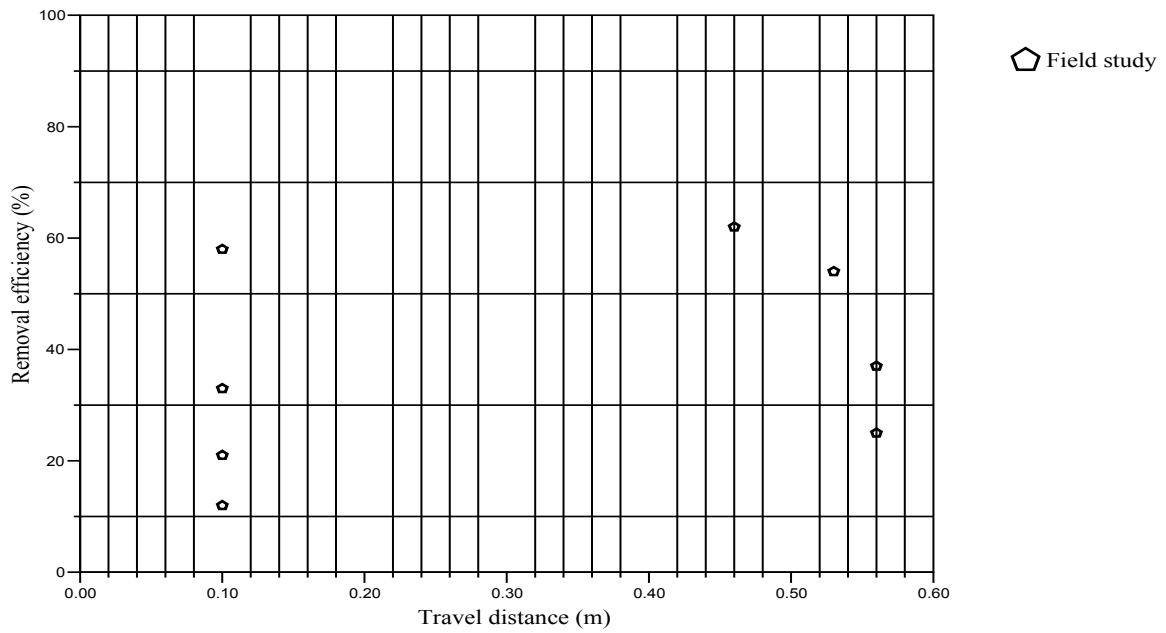


Figure 4.1 DOC removal efficiency vs. travel distance during soil aquifer treatment of primary effluents

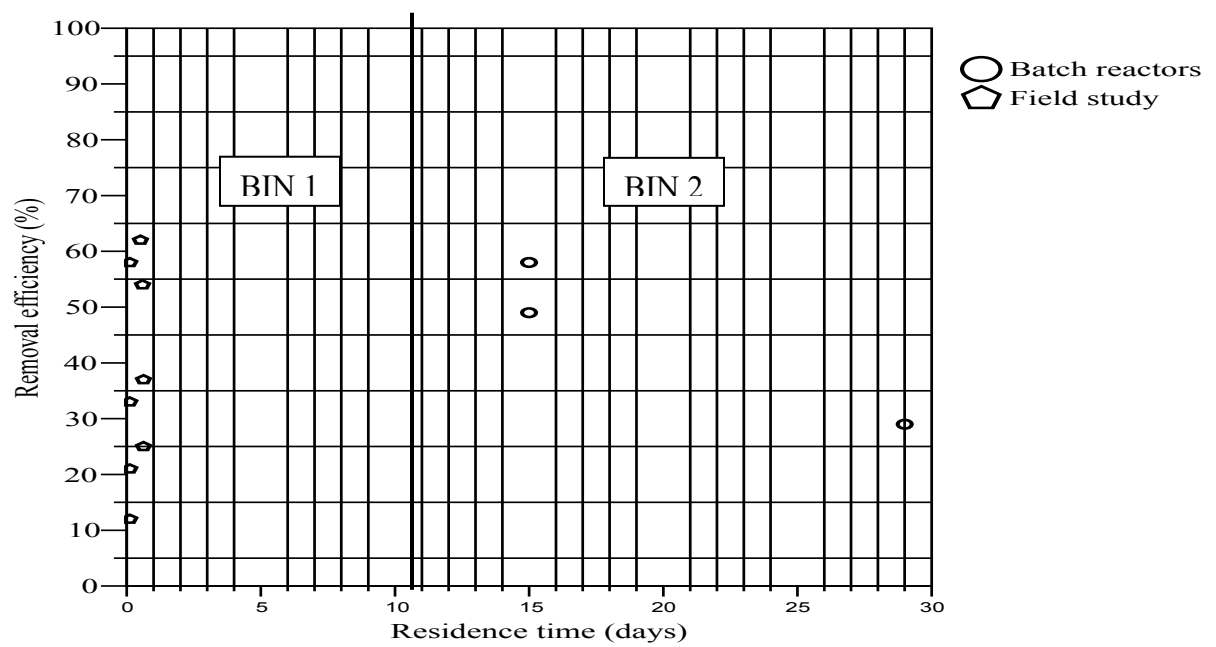


Figure 4.2 DOC removal efficiency vs. residence/travel time during soil aquifer treatment of primary effluents

Table 4.6 Analysis of DOC removal data for SAT systems treating primary effluents at different travel distances

Travel distance (m)	Removal efficiency (%)		Standard deviation (%)	No of results
	Range	Average		
<1	12-62	38	18	8

Table 4.7 Analysis of DOC removal data for SAT systems treating primary effluents at different residence/travel times

Residence/Travel time (days)	Removal efficiency (%)		Standard deviation (%)	No of results
	Range	Average		
1-10	12-62	38	18	8
10-30	29-58	45	15	3

Based on the data analysis shown on Tables 4.6 and 4.7 above and assuming that DOC is derived from infiltrates from the recharge source only and redox and biomass condition are sufficient to influence DOC removal, the guidelines were developed as shown in Tables 4.8 and 4.9.

Table 4.8 Guidelines for estimation of DOC removal from primary effluents during SAT with respect to travel distance

Influent quality (mg/L)	Travel Distance (m)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
24	≤1	10	40	60	4-15-
	>1	>10	>40	>60	

Table 4.9 Guidelines for estimation of DOC removal from primary effluents during SAT with respect to residence/travel time

Influent quality (mg/L)	Residence/travel time (day)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
9-35	1-10	10	40	60	7-21
	10-30	20	45	60	
	>30	>20	>45	>60	

4.3.2 NH₄-N removal and guidelines for estimation of water quality

Results presented and discussed in this section come from two SAT sites facilities in Mesa, Arizona and Ahmedabad in India. The Mesa SAT had attained a higher removal efficiency (up to 98%) because of a longer drying period that improved redox conditions leading to more ammonia nitrogen removal (Rice and Bouwer, 1984). Both SAT site systems provided desired quality of renovated water for unrestricted irrigation (Nema *et al.*, 2001; Rice and Bouwer, 1984).

Figures 4.3 and 4.4 show the removal of ammonia at different travel distance up to 1 m of the vadose zone for the different basins. The ammonia removal at the Ahmedabad SAT site was 50% at 25 m travel distance and travel time >10 days, these results were not included in the graph because of scale size in the graph. The analysis of ammonia removal during SAT is shown in Tables 4.10 and 4.11 followed by developed guidelines in Tables 4.12 and 4.13.

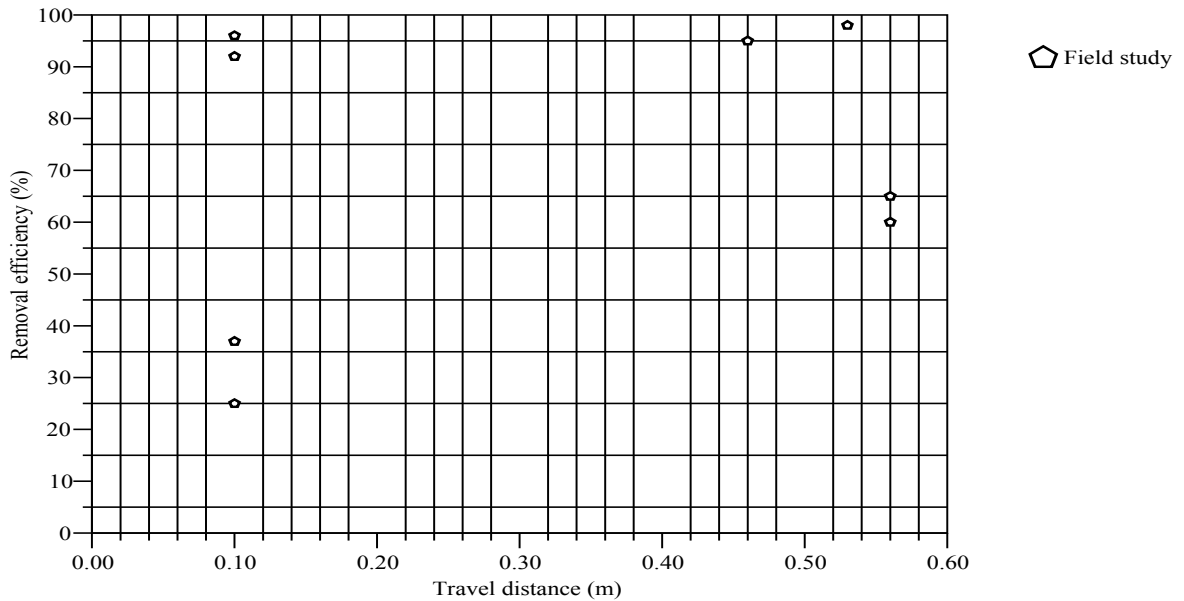


Figure 4.3 NH₄-N removal efficiency vs. travel distance during soil aquifer treatment of primary effluents

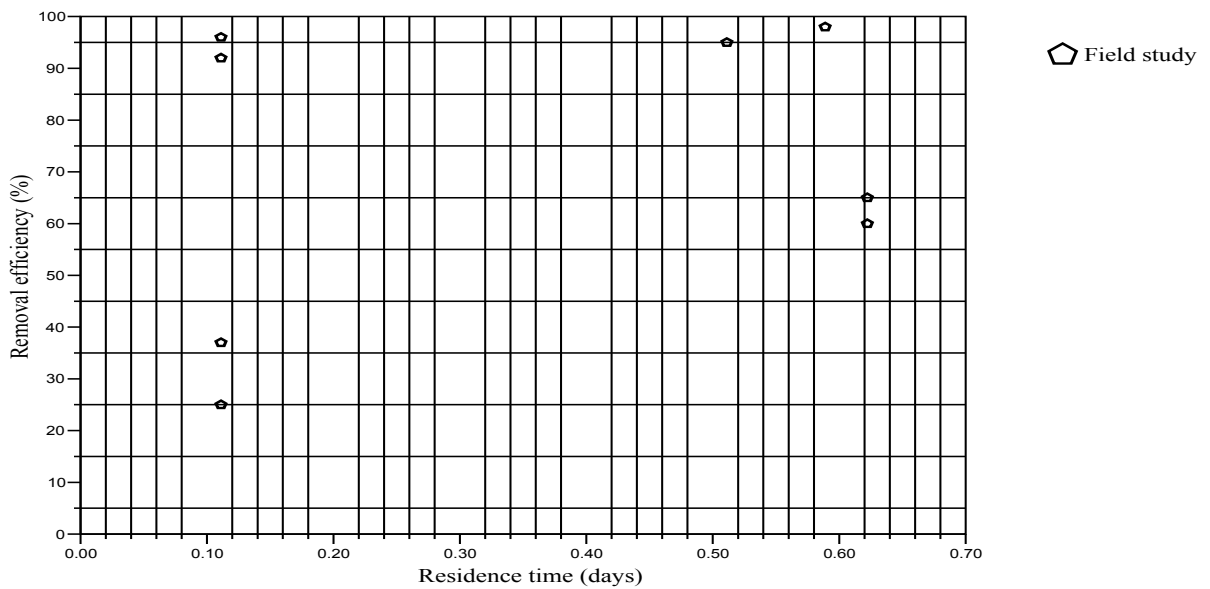


Figure 4.4 NH₄-N removal efficiency vs. residence/travel time during soil aquifer treatment of primary effluents

Table 4.10 Analysis of NH₄-N removal data for SAT systems treating primary effluents at different travel distance

Travel distance (m)	Removal efficiency (%)		Standard deviation (%)	No of results
	Range	Average		
<1	25-98	71	29	8

Table 4.11 Analysis of NH₄-N removal data for SAT systems treating primary effluents at different residence/travel times

Residence/Travel time (days)	Removal efficiency (%)		Standard deviation (%)	No of results
	Range	Average		
<1	25-98	71	29	8

Based on the data analysis shown on Tables 4.5 and 4.6 and assuming that NH₄-N is contributed by infiltrates from the recharge source only, redox and biomass condition are sufficient to influence NH₄-N removal, and that adsorbed ammonia breakthrough is not expected. Also assuming that under normal operating conditions ammonia removal during SAT increases with travel distance and residence/travel time. The guideline was developed as shown in Tables 4.7 and 4.8.

Table 4.12 Guidelines for estimation of NH₄-N removal from primary effluents during SAT with respect to distance

Influent quality (mg/L)	Travel distance (m)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
4-7	≤1	25	70	99	0.4-4
	>1	>25	>70	>99	

Table 4.13 Guidelines for estimation of NH₄-N removal from primary effluents during SAT with respect to residence/travel time

Influent quality (mg/L)	Residence/Travel time (days)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
4-7	≤1	25	70	99	0.4-4
	>1	>25	>70	>99	

4.3.3 PO₄-P removal and guidelines for estimation of water quality

Phosphorus is removed from wastewater by adsorption onto the soil (Lin and Banin, 2006). There is also a possibility of phosphorus uptake by bacteria (Idolevitch and Michail, 1984). Data from two SAT site and one soil column experiment were found in the literatures; one SAT site is located in Mesa, Arizona USA, and another in Ahmedabad India. The Ahmedabad site was in operation for 138 days while the Mesa site was in operation over many years. Figures 4.5 and 4.6 show the scatter of performance data for the Mesa site SAT plotted at travel distance <1 m. These SAT had different phosphorus removal efficiency that may generally be attributed to differences in infiltration rates,

travel distances and soil type. The Mesa site SAT had 4 basins operated under similar infiltration rates and sampling was done at different travel distances. One basin where samples were taken had loamy sand and other had sandy loam. Different removal efficiency were observed at different basins. Therefore differences in phosphorus removal efficiency are likely attributed to differences soil type and travel distance. The soil column was 2.75 m long packed with loamy sand. The phosphorus removal efficiency was about 70%. The analyses of performance of SAT systems are shown on Tables 4.14 and 4.15 and guideline for phosphorus removal on Tables 4.16 and 4.17.

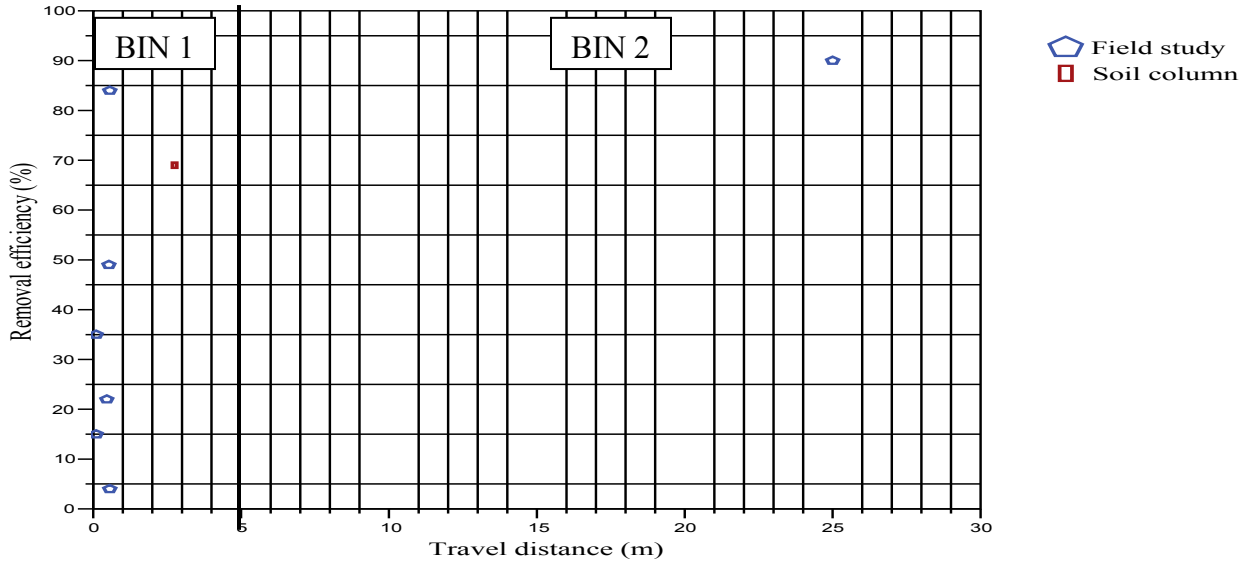


Figure 4.5. PO₄-P removal efficiency vs. travel distance during soil aquifer treatment of primary effluents

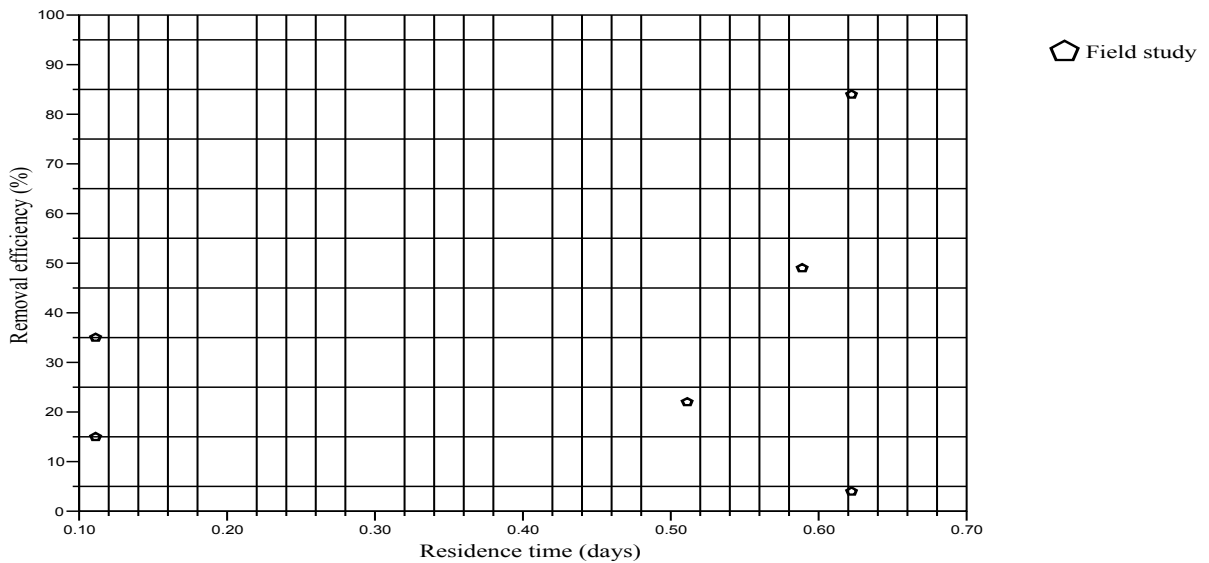


Figure 4.6 PO₄-P removal efficiency vs. residence travel time during soil aquifer treatment of primary effluents

Table 4.14 Analysis of PO₄-P removal data for SAT systems treating primary effluents at different travel distance

Travel distance (m)	Removal efficiency (%)		Standard deviation (%)	No of results
	Range	Average		
0.1-5	4-84	40	29	7

Table 4.15 Analysis of PO₄-P removal Data for SAT systems treating primary effluents at different residence/travel times

Residence/Travel time (m)	Removal efficiency (%)		Standard deviation (%)	No of results
	Range	Average		
<1	4-84	35	29	6

Based on the data analysis shown on table 4.14 and table 4.15 above and assuming that PO₄-P contribution is infiltrate from the recharge source only and that adsorbed PO₄-P break through is not expected the guideline was developed as shown in Tables 4.16 and 4.17.

Table 4.16 Guidelines for estimation of PO₄-P removal from primary effluents during SAT with respect to distance

Influent quality (mg/L)	Travel Distance (m)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
6-7	0.1-5	4	40	80	1-5
	>5	>4	>40	>80	

Table 4.17 Guidelines for estimation of PO₄-P removal from primary effluents during SAT with respect to residence/travel time

Influent quality (mg/L)	Residence/Travel time (days)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
6	<1	4	40	80	1-5
	>1	>4	>40	>80	

4.3.4 Trace organics removal and guidelines for estimation of water quality

Data for one site SAT which is located in Fort Devens, Massachusetts USA. The data were taken at one point at a distance of 7 m therefore no graph is shown. The trace organics which were measure includes; naphthalene, toluene, phenol anisole, benzene, terpeneol, cresol, phthalate, Indole, xylene compounds. The removal of trace organics during SAT was investigated. The removal of these trace organics by adsorption followed by biodegradation took place in the top 1 m of soil (Hutchins *et al.*, 1983) Refractory volatile organics like toluene, xylene, are mainly removed through adsorption and volatilisation mechanisms (Tomson *et al.*, 1981). The analysis of trace organic data is shown on Tables 4.18 and 4.19 and the guidelines developed shown on table 4.20 and

4.21.

Table 4.18 Analysis of trace organics removal data for SAT systems treating primary effluents at different travel distance

Travel distance (m)	Removal efficiency (%)		Standard deviation (%)	No of results
	Range	Average		
5-10	75-100	95%	8	16

Table 4.19 Analysis of trace organics removal data for SAT systems treating primary effluents at different residence/travel times

Residence/Travel time (m)	Removal efficiency (%)		Standard deviation (%)	No of results
	Range	Average		
8-12	75-100	95	8	16

Based on the data analysis shown on Tables 4.18 and 4.19 above, and assuming that volatile trace organic contributed from infiltrate from the recharge source only and the conditions allow adsorption and biodegradation of trace organics, The guideline for removal of volatile trace organic are developed as shown in Tables 4.20 and 4.21.

Table 4.20 Guidelines for estimation of trace organics removal from primary effluents during SAT with respect to distance

Travel distance (m)	Removal efficiency (%)		
	Minimum	Average	Maximum
5-10	75	95	100
>10	>75	>95	100

Table 4.21 Guidelines for estimation of trace organics removal from primary effluents during SAT with respect to residence/travel time

Residence/Travel time (days)	Removal efficiency (%)		
	Minimum	Average	Maximum
8-12	75	95	100
>10	>75	>95	100

4.3.5 Microbe removal and guidelines for estimation of water quality

Control of pathogens is the predominant concern for reuse of renovated water (Asano and Cotruvo, 2004). Data on removal of microbes during SAT for one field site located in Ahmedabad in India and 2 soil columns studies are presented and discussed in this section. One soil column was 2.75 m in depth and the other was 2.50 m in depth. The former was packed with loamy sand and the later was packed with sandy loam, the influent to soil column that was 2.75 m in depth had a higher concentration of microbes. The effluent quality of a deeper column had a concentration of 0 to about 200 MPN/100ml of total coliform while the effluent of the 2.50 m column had a

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concentration of microbes 0 to about 50 MPN/100 ml of faecal coliform which shows that both columns achieved good effluent quality for unrestricted irrigation under tropical conditions. The quality requirements for unrestricted irrigation is <100 fecal coliforms per 100 mL (Buiteman, 2005). The 2.75 m column also removed the polio viruses below the detection limit. The removal of microbes is shown on Figures 4.7 and 4.8 and analysis of removal of microbes during SAT is shown on Tables 4.22 and 4.23.

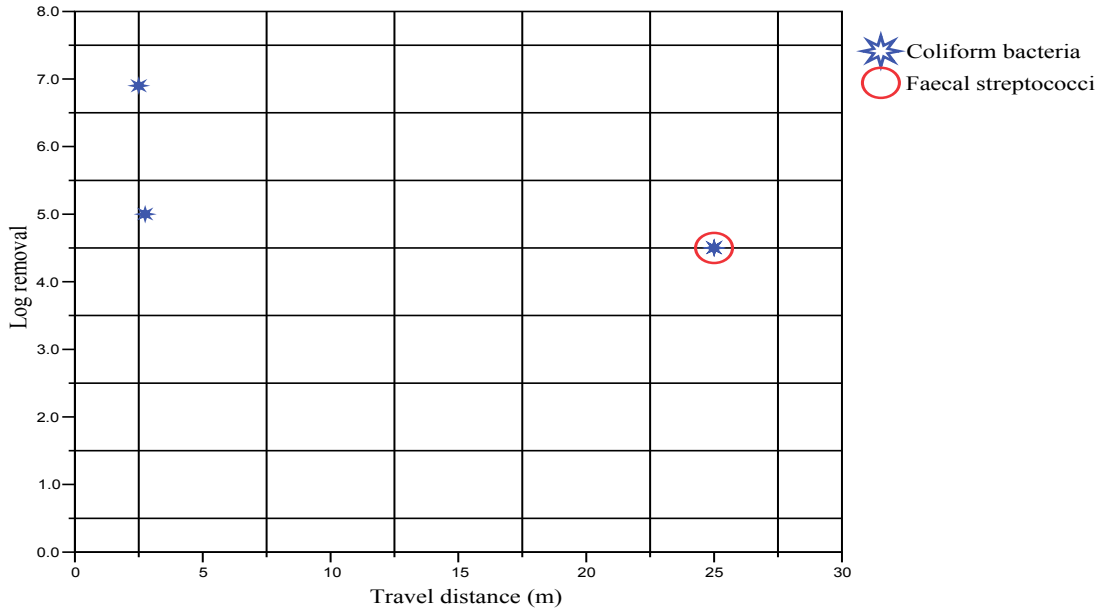


Figure 4.7 Microbe removal efficiency vs. travel distance during soil aquifer treatment of primary effluents

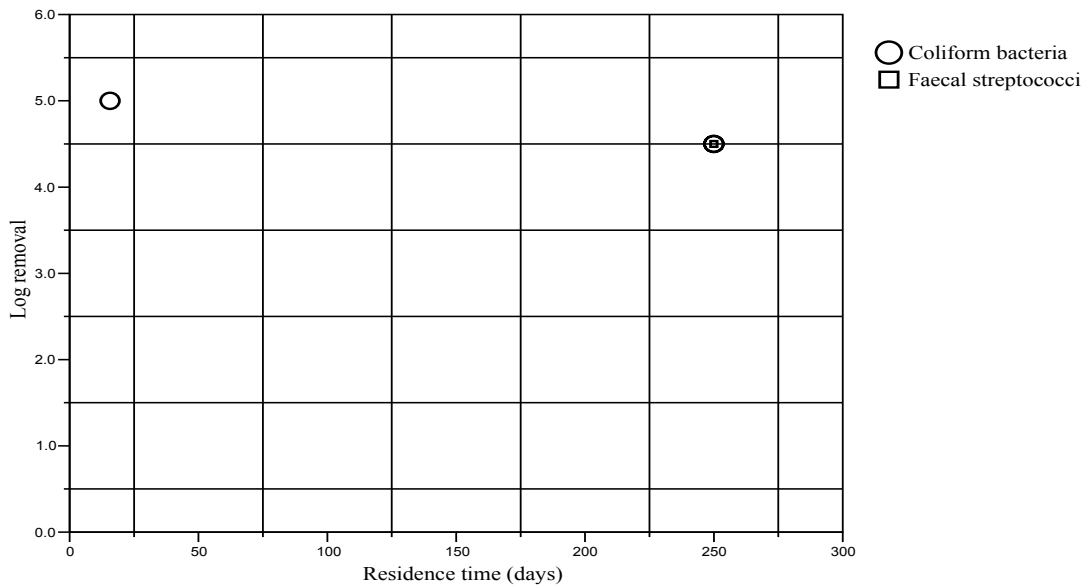


Figure 4.8 Microbe removal efficiency vs. residence/travel time during soil aquifer treatment of primary effluents

Table 4.22 Analysis of microbe removal data for SAT systems treating primary effluents at different travel distance

Microbe	Travel Distance (m)	Log removal		Standard deviation (log)	No of results
		Range	Average		
Coliform	1-5	5.0-6.9	5.95	1.3	3
Polio virus	1-5	4.57-No detection	-		1

Table 4.23 Analysis of microbe removal data for SAT systems treating primary effluents at different residence/travel times

Microbe	Residence/Travel time (days)	Log removal			No of results
		Range	Average	Standard deviation (log)	
Coliform	10-250	5.0-6.9	5.95	1.3	3
Polio virus	1-5	4.57-No detection	-		1

Based on the data analysis shown on Table 4.22 and 4.23 above and assuming that microbes are contributed via infiltrates from the recharge source only, and microbe removal increases with travel distances and travel time. The guideline for removal of microbe are developed as shown in Tables 4.24 and 4.25.

Table 4.24 Guidelines for estimation of microbe removal from primary effluents during SAT with respect to distance

Microbe	Travel distance (m)	Log removal		
		Minimum	Average	Maximum
Coliforms	1-5	5	6	7
	>5	>5	>6	7

Table 4.25 Guidelines for estimation of microbe removal from primary effluents during SAT with respect to residence/travel time

Microbe	Residence/Travel time (days)	Log removal		
		Minimum	Average	Maximum
Coliforms	<10	<5	<6	<7
	>10	>5	>6	>7

Table 4.26 Summary of guidelines for estimation of contaminants removal from primary effluents during SAT with respect to travel distance and residence/travel time

Contaminant	Influent quality (mg/L)	Travel Distance (m)	Removal efficiency (%)			Effluent quality (mg/L)	
			Minimum	Average	Maximum		
DOC	24	≤1	10	40	60	4-15	
		>1	>10	>40	>60		
	9-35	Residence/travel time (day)	1-10	10	40	60	7-21
			10-30	20	45	60	
		>30	>20	>45	>60		
NH ₄ -N	Influent quality (mg/L)	Travel distance (m)	Removal efficiency (%)			Effluent quality (mg/L)	
			Minimum	Average	Maximum		
	4-7	≤1	25	70	99	0.4-4	
		>1	>25	>70	>99		
	4-7	Residence/Travel time (days)	≤1	25	70	99	0.4-4
			>1	>25	>70	>99	
PO ₄ -P	Influent quality (mg/L)	Travel Distance (m)	Removal efficiency (%)			Effluent quality (mg/L)	
			Minimum	Average	Maximum		
	6-7	0.1-5	4	40	80	1-5	
		>5	>4	>40	>80		
	6	Residence/Travel time (days)	≤1	4	40	80	1-5
			>1	>4	>40	>80	
Trace organics	Influent quality (mg/L)	Travel distance (m)	Removal efficiency (%)			Effluent quality (mg/L)	
			Minimum	Average	Maximum		
	Not provided	5-10	75	95	100	Not provided	
		>10	>75	>95	100		
	Not provided	Residence/Travel time (days)	8-12	75	95	100	Not provided
			>10	>75	>95	100	

Summary of guidelines for estimation of contaminants removal from primary effluents during SAT with respect to travel distance and residence/travel time (continue)

Contaminants	Travel distance (m)	Log removal		
		Minimum	Average	Maximum
Coiliform and Faecal streptococci	1-5	5	6	7
	>5	>5	>6	7
	Residence/Travel time (days)	Log removal		
		Minimum	Average	Maximum
>10	>5	>6	>7	

It is to be noted that while making a quick assessment of the SAT system using these guidelines, the guideline for microbe removal which is most crucial should be given a priority. However other guidelines should be applied according to needs. It is recommended to choose maximum distances stated in the guidelines in order to reduce risks of pumping water which is not sufficiently treated during SAT.

4.4 Attenuation of contaminants from secondary effluents and guidelines development

4.4.1 DOC removal and guideline for estimation of water quality

SAT data for 12 soil column experiments, 14 batch experiments and 4 field sites are presented and discussed. Two SAT Site are located in USA (Tucson and Mesa, Arizona) and other two field sites are located Israel (Yavne and Soreq). Tucson field site received chlorinated effluent. Different types of soil mostly collected from existing potential recharge sites were used in soil columns and batch experiments simulating SAT systems. Soil types packed in soil columns were sandy loam (4), poorly graded sand (3) silty sand (1), poorly graded silty sand (1), and silica sand (4). The batch SAT used sandy loam (4), poorly graded silty sand (3), poorly graded sand (7) and sandy soil (3). Laboratory and field scale soil aquifer treatment (SAT) systems were recharged with secondary effluents from different wastewater treatment facilities namely trickling filters, activated sludge system and aerated lagoons.

The SAT site systems consisted of surface spreading basins with vadose zone depths ranging from 15 to 38 m and recovery wells located approximately 40 m to 1000 m down gradient from surface spreading basins. The travel and residence times ranged from approximately 1 day to 30 days and 1 day to 18 months in laboratory scale and SAT sites respectively. Simulated SAT soil columns were 0.3 to 5 m in depth. The general trend for DOC removal during SAT showed an increase with travel distance and residence/travel time. Figure 4.9 and 4.11 show the performance of SAT with respect to different distances and residence/travel times respectively.

The majority of performance data appear in bin 1 (Figures 4.9 and 4.11) show the DOC removal achieved by simulated SAT soil columns. The rest of the bins present the DOC removal in the vadose zone of SAT sites. The DOC removal in Bin 1 is approximately

15%-70%, this difference is attributed to a number of factors which includes infiltration rates, travel time, organic carbon content of soil, composition of DOC fractions and redox conditions (Kanarek *et al.*, 1993; Katukiza, 2006; Quanrud *et al.*, 1996a; Quanrud *et al.*, 1996b; Quanrud *et al.*, 2003c). Sweet water recharge facility in Arizona (Field site SAT) system removed DOC from secondary effluents via percolation through the vadoze zone to a concentration of about 1mg/L which is low compared to groundwater DOC which is about 2 mg/L. Generally the DOC removal of more than 70% was achieved at short term SAT of approximately 1 month to and long term SAT of more than 18 months and travel distance of about 15m to 1000m in field sites. The performance of SAT with respect to travel/residence time is shown in Figure.4.11. The major purification of the effluent in site SAT took place during the vertical flow in the vadose zone (Fox *et al.*, 2001b; Quanrud *et al.*, 2003c; Yoo *et al.*, 2006). Apparent decrease in DOC removal in bin 3 and 4 in Figures 4.9 and 4.11 respectively may be the influence of DOC from other sources or leaching of DOC from soil. Figures 4.9 and 4.12 shows the 5, 25, 75, 95 percentile and median of the data used to develop guidelines for DOC removal from secondary effluents with respect to travel distance and travel time respectively. The analysis of performance of SAT is shown on Tables 4.27 and 4.28.

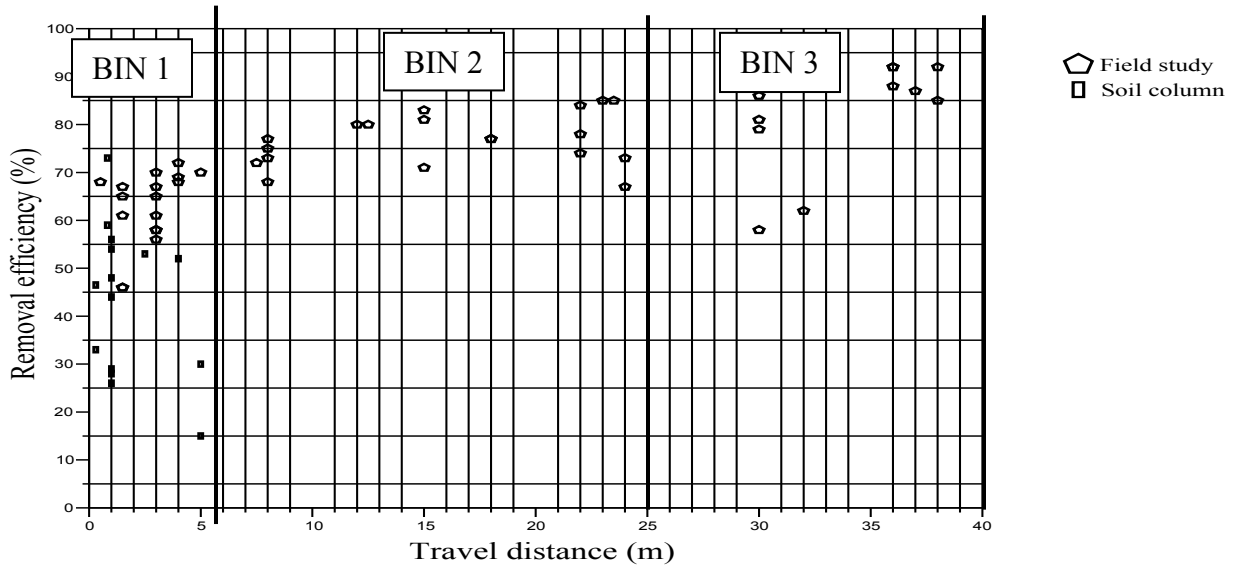


Figure 4.9 DOC removal efficiency vs. travel distance during soil aquifer treatment of secondary effluents

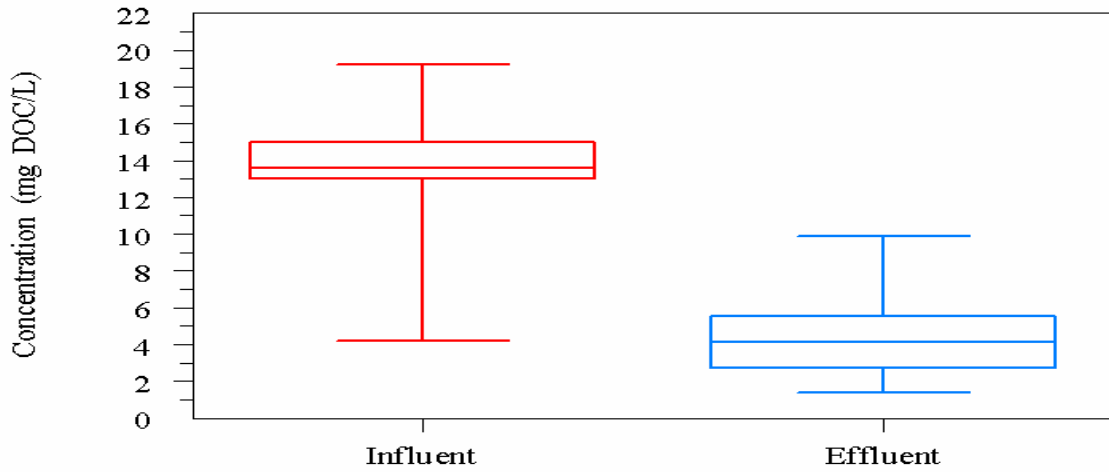


Figure 4.10 Box and Whisker graph for data used in guidelines for DOC removal with respect to travel distance during soil aquifer treatment of secondary effluents

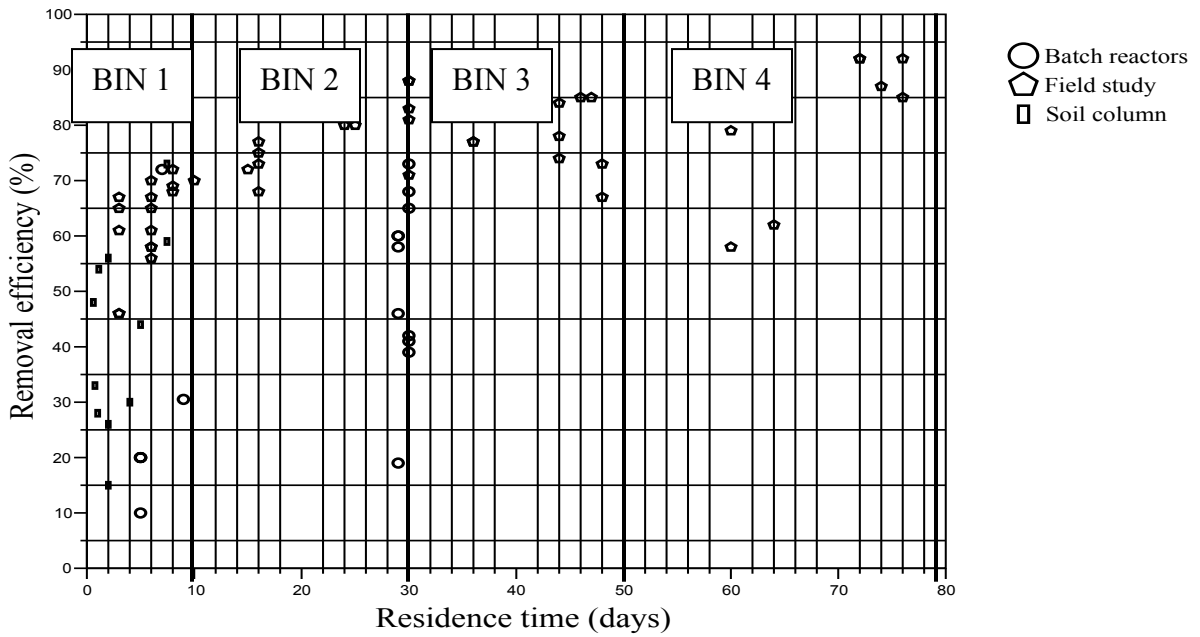


Figure 4.11 DOC removal efficiency vs. residence/travel time during soil aquifer treatment of secondary effluents

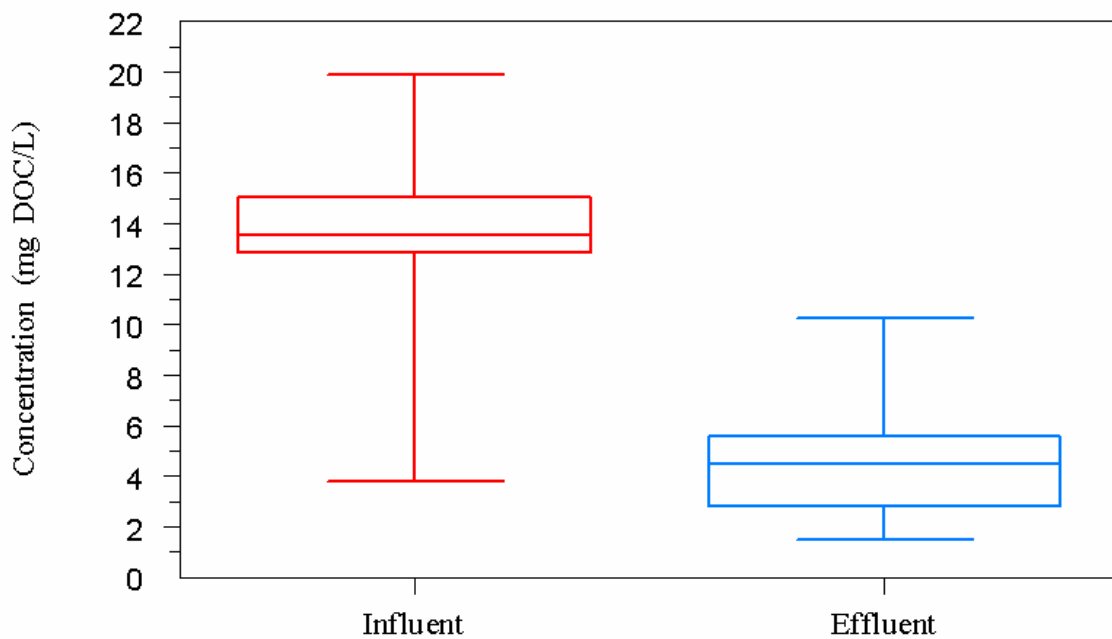


Figure 4.12 Box and Whisker graph for data used in guidelines for DOC removal with respect to travel time during soil aquifer treatment of secondary effluents

Table 4.27 Analysis of DOC removal data for SAT systems treating secondary effluents at different travel distances

Travel Distance (m)	Removal efficiency (%)		Standard deviation (%)	No. of results
	Range	Average		
1-5	15-73	52	15	29
5-25	67-88	79	7	12
>25	58-93	80	11	12

Table 4.28 Analysis of DOC removal data for SAT systems treating secondary effluents at different residence/travel times

Residence/travel time (days)	Removal efficiency (%)		Standard deviation (%)	No. of results
	Range	Average		
1-10	10-73	49	18	34
10-30	19-88	58	21	19
30-50	67-85	77	7	6
>50	58-94	80	12	12

Based on the data analysis shown on Tables 4.27 and 4.28 above, and assuming that DOC is contributed by infiltrates from the recharge source only, and redox and biomass conditions are sufficient to influence DOC removal. Also assuming that in general under the normal operating conditions DOC removal increases with travel distance and residence/travel time, the guideline were developed as shown in Tables 4.29 and 4.30 below.

Table 4.29 Guidelines for estimation of DOC removal from secondary effluents during SAT with respect to travel distance

Influent quality (mg/L)	Travel distance (m)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
4-15	1-5	15	50	70	1.5-10
	5-25	70	80	90	
	>25	≥70	≥80	≥90	

Table 4.30 Guidelines for estimation of DOC removal from secondary effluents during SAT with respect to residence/travel time

Influent quality (mg/L)	Residence/travel time (days)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
2-24	1-10	10	50	70	1.5-16
	10-30	20	60	90	
	30-50	70	80	90	
	>50	≥70	≥80	≥90	

4.4.2 NH₄-N removal and guideline for estimation of water quality

NH₄-N removal data from seven SAT studies (five soil columns (1-2 m in depth) simulating SAT and two field sites) are presented and discussed. Soil column packed with different types of native soils and soil from potential field site as media for treating wastewater were used to simulate SAT. The soil type packed in columns and number shown in brackets includes poorly graded sand (1), Konawa sand (1), gravelly sand clay (1), lomey sand (1) and sandy lime (1). Ammonia was removed within the top few feet (1-3 feet) of both soil columns and field SAT via adsorption followed by nitrification where oxic conditions were predominant (Fox *et al.*, 2001b; Idolevitich and Michail, 1984; Miller *et al.*, 2006). Ammonia is converted nitrate during SAT which may lead to increased nitrate concentration in groundwater (Reemtsma *et al.*, 2000; Viswanathan *et al.*, 1999). Removal of ammonia was higher in the soil column with sandy soil. The lesser removal in efficiency in bin 1 and bin 2 (Figures 4.13 and 4.15) is likely attributed to leaching of ammonia from the soil due to increased infiltration rate or longer flooding periods. Ammonia breakthrough can occur under conditions of continuous flooding (Idolevitich and Michail, 1984). The soil column with sand media had higher removal efficiency which was attributed to the presence of more pore spaces that allowed more oxygen resulting in higher nitrification capacity. However it should be noted that ammonia removal is predominantly biochemical process which consumes oxygen therefore the fate and transport of ammonia nitrogen depend on availability of oxygen, nitrifiers and organic carbon (Cha *et al.*, 2005; Fox *et al.*, 2001b; Miller *et al.*, 2006). Figures 4.14 and 4.16 show the 5, 25, 75, 95 percentile and median of data used to develop guidelines for ammonia removal with respect to travel distance and travel time respectively. The analysis for ammonia removal data is shown on Tables 4.31 and 4.32.

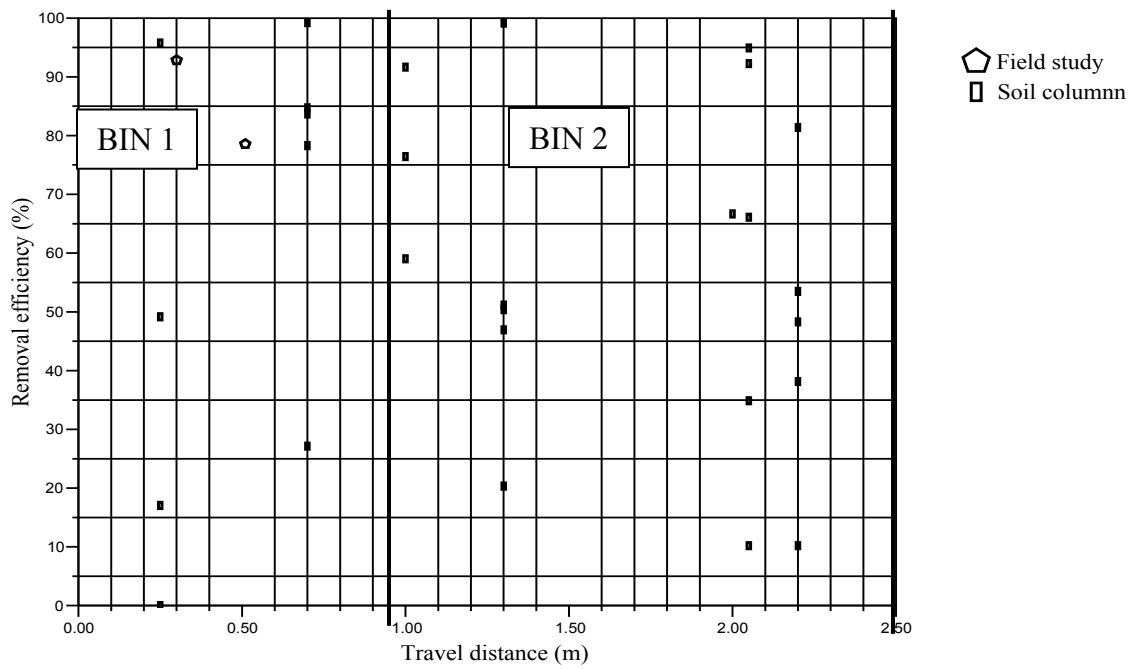


Figure 4.13 $\text{NH}_4\text{-N}$ removal efficiency vs. travel distance during soil aquifer treatment of secondary effluents

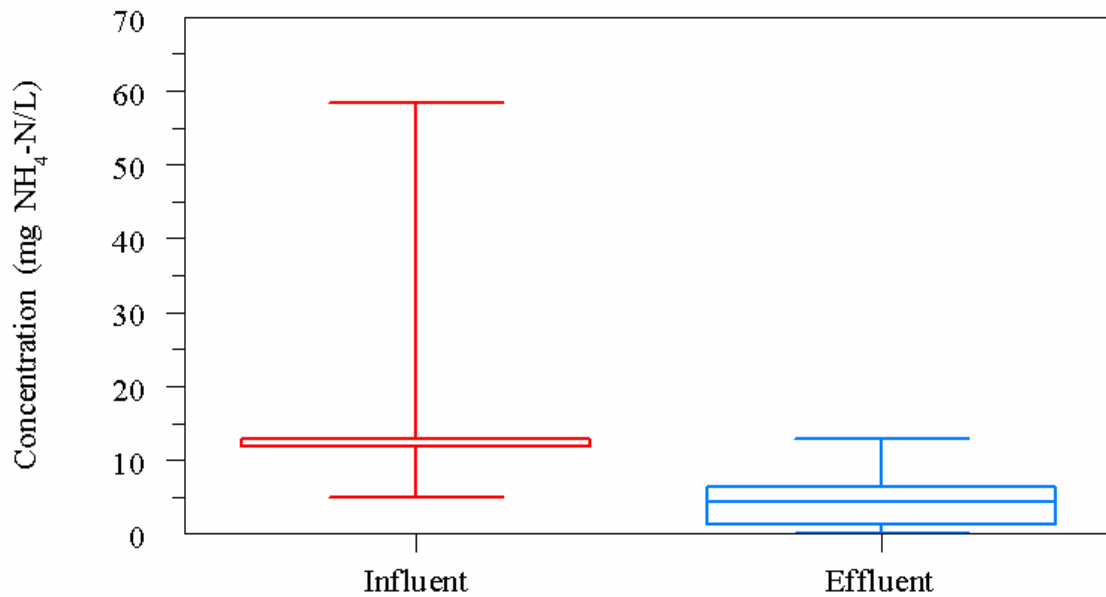


Figure 4.14 Box and Whisker graph for data used in guidelines for $\text{NH}_4\text{-N}$ removal with respect to travel distance during soil aquifer treatment of secondary effluents

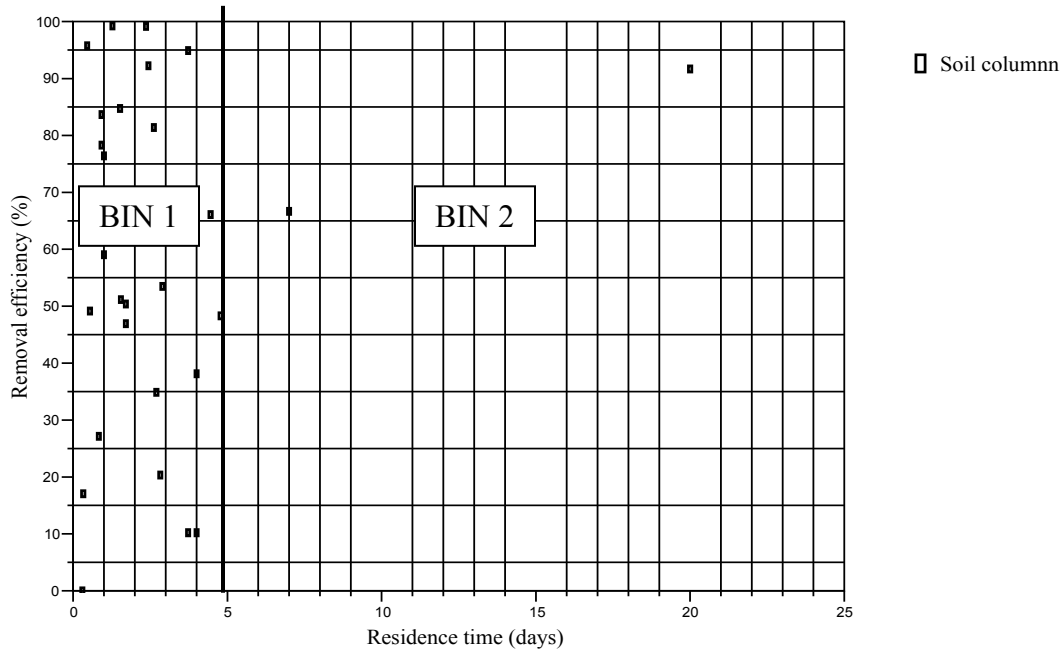


Figure 4.15. $\text{NH}_4\text{-N}$ removal efficiency vs. travel distance during soil aquifer treatment of secondary effluents

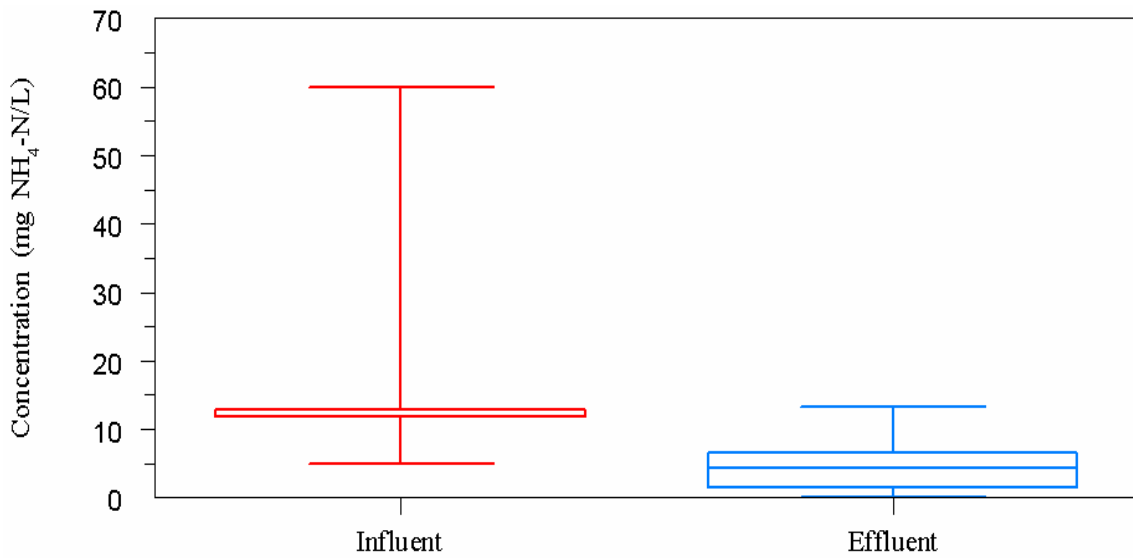


Figure 4.16 Box and Whisker graph for data used in guidelines for $\text{NH}_4\text{-N}$ removal with respect to travel time during soil aquifer treatment of secondary effluents

Table 4.31 Analysis of NH₄-N removal data for SAT systems treating secondary effluents at different travel distances

Travel distance (m)	Removal efficiency (%)		Standard deviation (%)	No. of results
	Range	Average		
0.3-1.0	17-99	70	31	16
1.0-2.5	10-99	56	29	17
>2.5	94-100	97	3	11

Table 4.32 Analysis of NH₄-N removal data for SAT systems treating secondary effluents at different residence/travel times

Residence/Travel time (days)	Removal efficiency (%)		Standard deviation (%)	No. of results
	Range	Average		
1-5	17-99	63	31	32
5-25	67-94	91	10	8
>25	99-100	100	0.2	5

Based on data analysis above and, assuming that ammonia contribution for SAT system is derived from infiltrate from recharge source only, and in general under the normal operating conditions ammonia removal increases with travel distance and residence/travel time, guidelines for estimation of ammonia removal with respect to travel distance and travel/residence time are developed, as shown in Tables 4.33 and 4.34, respectively

Table 4.33 Guidelines for estimation of NH₄-N removal from secondary effluents during SAT with respect to residence/travel time

Influent quality (mg/L)	Residence/Travel time (days)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
5-60	1-5	20	60	99	0-20
	5-25	70	90	>99	
	>25	>70	>90	>99	

Table 4.34 Guidelines for estimation of NH₄-N removal from secondary effluents during SAT with respect to distance

Influent quality (mg/L)	Travel distance (m)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
5-60	0.3-1.0	20	70	99	0-20
	1.0-2.5	50	80	99	
	>2.5	>50	>80	>99	

4.4.3 NO₃-N removal and guideline for estimation of water quality

SAT data for nitrate removal during SAT which are presented and discussed in this section includes data from five soil (1-2m long) columns simulating SAT and three SAT field sites. The soil column SAT were packed with different types of native soils and soil

from a potential field site as media for treating wastewater which include poorly graded sand (2), Konawa sand (1), gravely sand clay (1) and sandy lime (1). SAT systems were recharged with secondary effluents which were pretreated by aerated lagoons, oxidation and ammonia stripping ponds, trickling filters and activated sludge systems. Nitrate was produced through a biochemical process in which ammonia was nitrified under oxic condition by nitrifiers during SAT in field sites. During SAT, nitrate was removed by partial denitrification under anoxic conditions during the vertical flow in the vadose zone. Miller *et al.*, 2006 found that the local vadose zone remained anoxic at a depth great than 1.5m below land surface of the SAT site they investigated. Soil column SAT with a sand clay media consistently demonstrated greater partial denitrification than did soil column SAT with a more sand content, apparently because of the lesser amount of available oxygen stored in the soil profile. However, some denitrification occurred in anaerobic pockets in predominantly aerobic area in soil columns. For complete denitrification to occur it is important that recharged effluent has carbon: nitrogen ratio of 2-3:1 or more (Fox *et al.*, 2001b), SAT systems often do not have sufficient organic carbon for complete denitrification.

Figures 4.17 and 4.19 show the performance of SAT systems removing nitrate with respect to travel distance and Residence/travel time respectively. Figure 4.18 shows the 5, 25, 75, 95 percentile and median of data used for development of guidelines. Analysis of nitrate removal during SAT is shown on Tables 4.35 and 4.36 followed by guidelines in Tables 4.37 and 4.38 developed based on these analyses. However nitrate has demonstrated persistence to long term SAT (1020m and travel time 6-12 months) in Dan region (Israel) field site possibly because of lack of sufficient organic matter to enable denitrification. In Tucson (USA) SAT site removal of nitrate was achieved at an average efficiency of about 40% at a travel distance of 100ft below surface (BLS) below one of the three recharge basins. In the other recharge basins nitrate was slightly removed by about 10% at travel distance of 125 ft (BLS) and nitrate increased 10 times at travel distance of 10ft (BLS) in the third recharge basin. Recovered water is used for unrestricted irrigation of agricultural crops; therefore there is no need to reduce the nitrogen load. Where potable reuse is needed, then the nitrate load in SAT product water has to be significantly reduced.

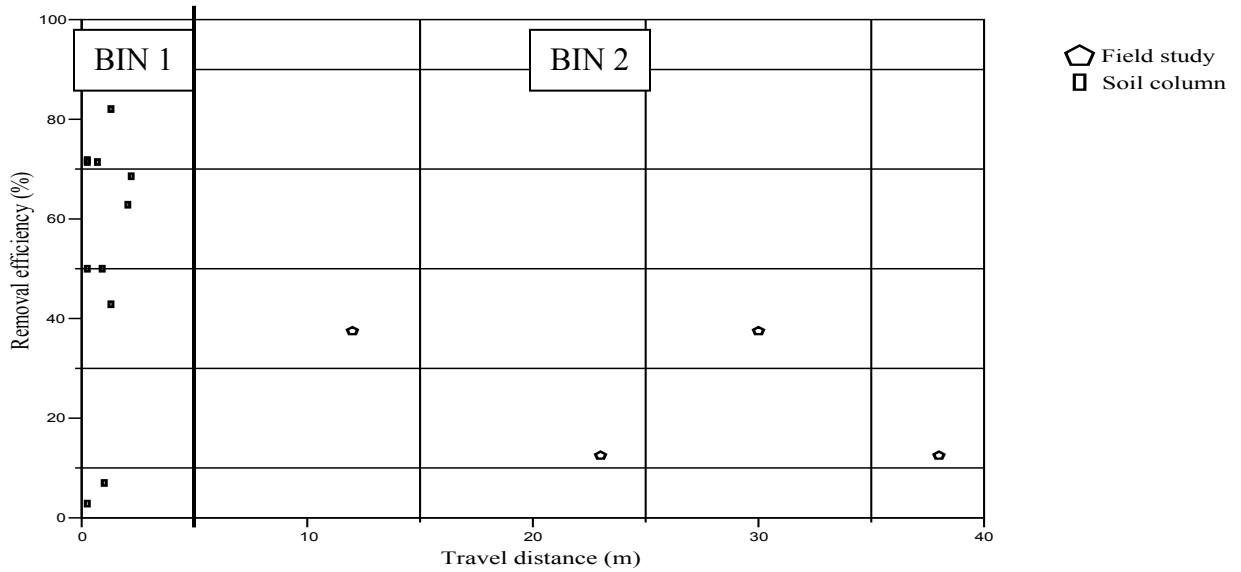


Figure 4.17 NO₃-N removal efficiency vs. travel distance during soil aquifer treatment of secondary effluents

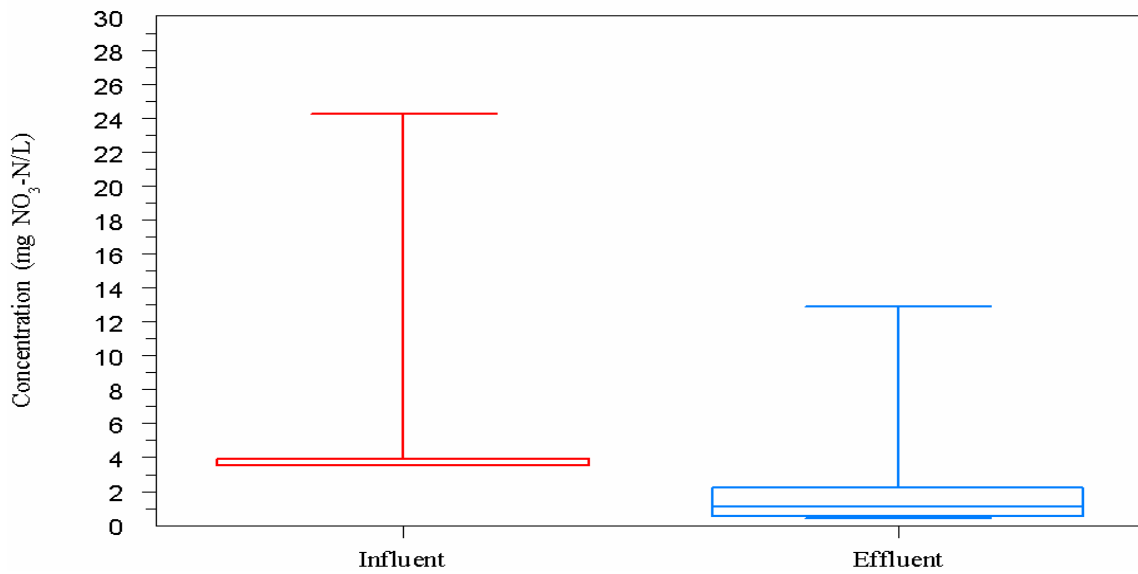


Figure 4.18 Box and Whisker graph for data used in guidelines for NO₃-N removal with respect to travel distance and travel time during soil aquifer treatment of secondary effluents

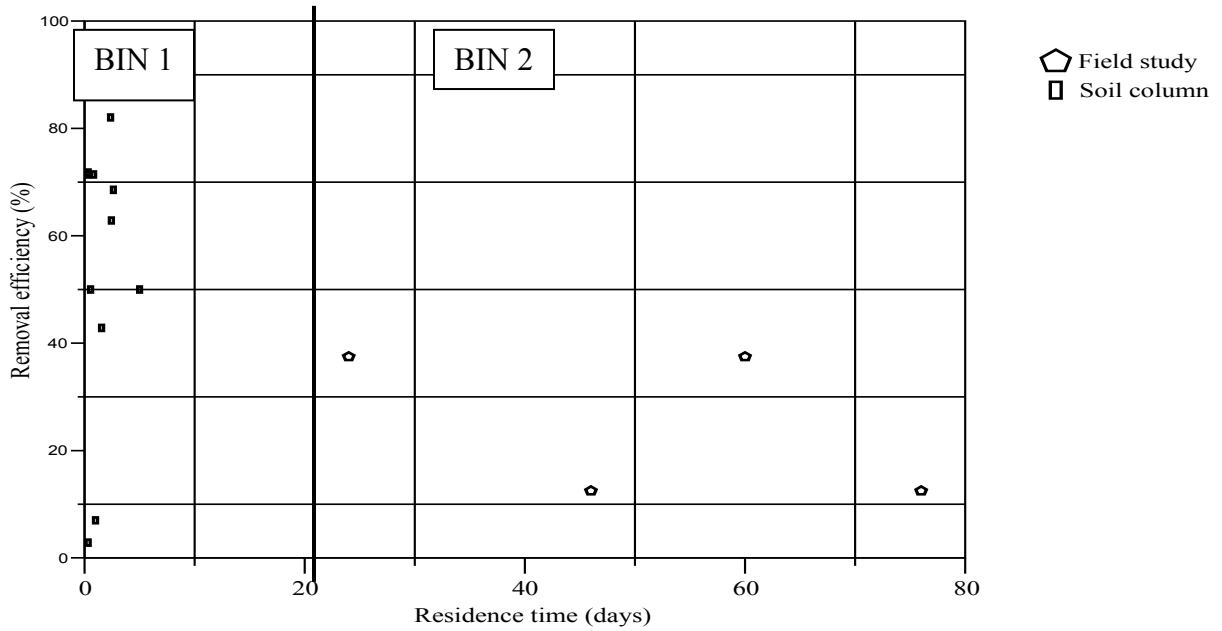


Figure 4.19 NO₃-N removal efficiency vs. residence/travel time during soil aquifer treatment of secondary effluents

Table 4.35 Analysis of NO₃-N removal data for SAT systems treating secondary effluents at different travel distances

Travel distance (m)	Removal efficiency (%)		Standard deviation (%)	No. of results
	Range	Average		
0.25-5	3-90	62	27	15
5-38	13-38	25	14	4

Table 4.36 Analysis of NO₃-N removal Data for SAT systems treating secondary effluents at different residence/travel time

Residence/travel time (days)	Removal efficiency (%)		Standard deviation (%)	No. of results
	Range	Average		
0.3-10	3-90	62	27	15
10-76	13-38	25	14	4

Based on the above analysis assuming that reclaimed water is completely nitrified and therefore nitrate is not produced during SAT and that there is sufficient biomass and organic matter for heterotrophic denitrification, and that anoxic condition is predominant therefore the guideline for Nitrate removal was developed as shown Tables 4.37 and 4.38.

Table 4.37 Guidelines for estimation of NO₃-N removal from secondary effluents during SAT with respect to travel distance

Influent quality (mg/L)	Travel distance (m)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
3.5-30.0	1-5	3	60	90	0.4-15
	>5	>3	>60	>90	

Table 4.38 Guidelines for estimation of NO₃-N removal from secondary effluents during SAT with respect to residence/travel time

Influent quality (mg/L)	Residence/Travel time (days)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
3.5-30.0	1-10	3	60	90	0.4-15
	>10	>3	>60	>90	

4.4.4 PO₄-P removal and guideline for estimation of water quality

Excellent phosphorus removal occurred during SAT. Results for four SAT sites and one soil column (2.75 m in depth) are presented and discussed in this section. The SAT site systems are located in Tucson and Phoenix in Arizona USA and Yavne and Soreq Israel. The soil column used in simulating SAT was packed with loamy sand, and removed 66% of phosphorus from the influent. SAT site in Israel with recovery wells and monitoring well located at travel distance of approximately 45 m-1500 m has maintained higher removal phosphorus up to more than 99% over many years. There is no evidence of phosphorus breakthrough in Israel SAT field sites over many years of operation. However it should be noted that phosphorus is mainly removed by adsorption and therefore not sustainable. Some SAT site product water had a concentration of 0.02 mg/L which is in the range obtained in natural groundwater (Crites, 1985). Phosphorus removal increased as infiltration rate decreased. Figures 4.20 and 4.21 show the performances of SAT systems which are mostly higher than 90% in bin 1 and more than 99% in bin 2 of Figure 4.20. The performance of SAT field sites presented in Figure 4.21 bin 2 is comparable at different distances. Furthermore, recovery water is used for unrestricted irrigation of agricultural crops; therefore there is no need to reduce the phosphorus load. Where potable reuse is needed then phosphorus load in SAT product water has to be significantly reduced to control biostability. The analysis of phosphorus removal data is shown on Tables 4.39 and 4.40.

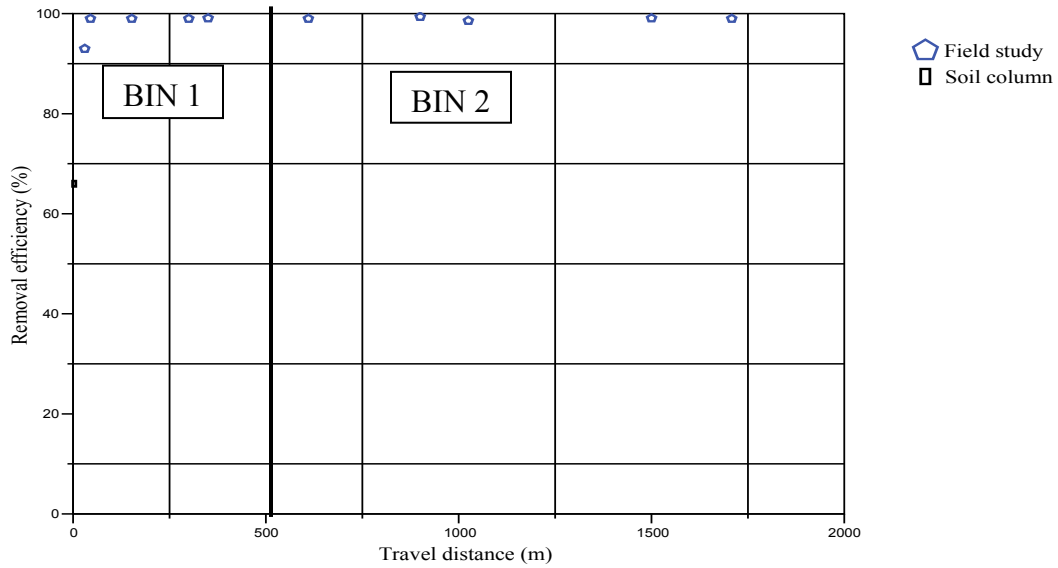


Figure 4.20 PO₄-P removal efficiency vs. travel distance during soil aquifer treatment of secondary effluents

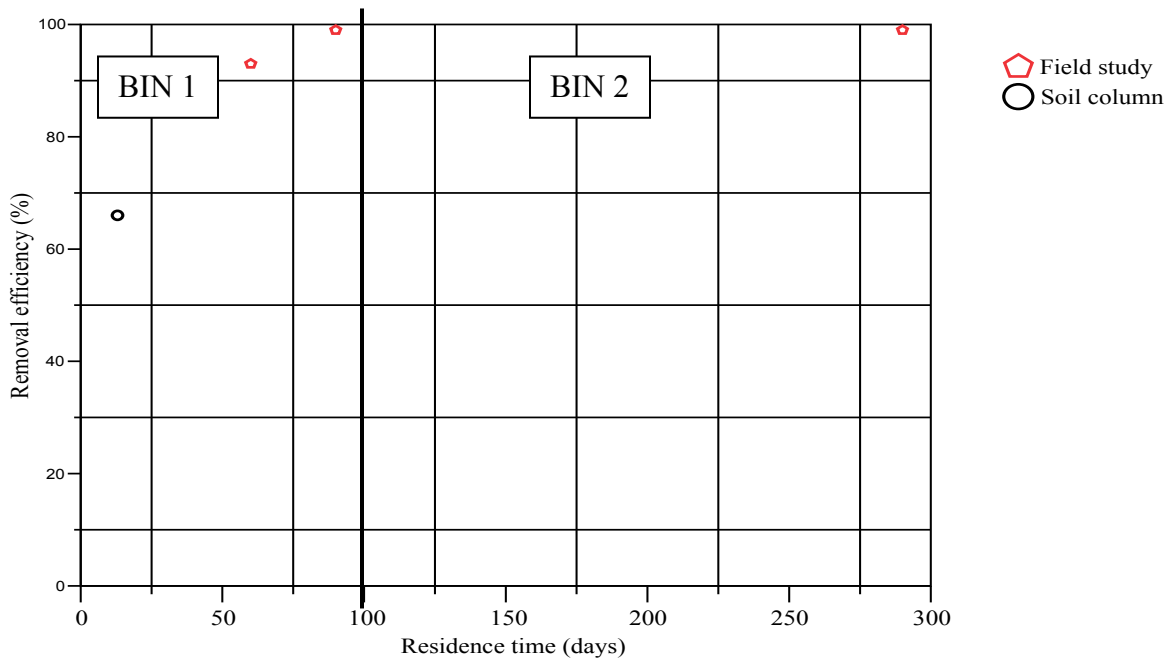


Figure 4.21 PO₄-P removal efficiency vs. residence/ travel time during soil aquifer treatment of secondary effluents

Table 4.39 Analysis of PO₄-P removal data for SAT systems treating secondary effluents at different travel distances

Travel distance (m)	Removal efficiency (%)		Standard deviation (%)	No. of results
	Range	Average		
1-500	66-99	92	13	6
>500	98.6-99.4	99	0.3	5

Table 4.40 Analysis of PO₄-P removal data for SAT systems treating secondary effluents at different residence/travel time

Residence/Travel time (days)	Removal efficiency (%)		Standard deviation (%)	No. of results
	Range	Average		
1-100	66-99	86	18	3
>100	98.6-99.5	99.4	0.2	8

Based on the data analysis shown on Tables 4.41 and 4.42 above and assuming that phosphorus is contributed via infiltrate from the recharge source only, and adsorbed phosphorus breakthrough is not expected, Guidelines were developed as shown in Tables 4.41 and 4.42.

Table 4.41 Guidelines for estimation of PO₄-P removal from secondary effluents during SAT with respect to travel distance

Influent quality (mg/L)	Travel distance (m)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
2-12	1-500	60	80	99	0.01-0.03
	>500	99	99	>99	

Table 4.42 Guidelines for estimation of PO₄-P removal from secondary effluents during SAT with respect to residence/travel time

Influent quality (mg/L)	Travel time (days)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
2-12	1-100	60	80	99	0.01-0.03
	>100	99	99	>99	

4.4.5 Trace organics removal and guideline for estimation of water quality

The trace organics discussed in this section are EDTA, NTA, NDC, APEC, EDC, Pharmaceuticals (Carbamazepine, Gemfibrozil, Primidone, Diclofenac, Ibuprofen, Ketoprofen, Naproxen, Fenoprofen, and Propyphenazone) and refractory volatile organics that include benzene compounds like Alkylbenzene, Alkoxyaromatics, dichlorobenzene and trichlorobenzene). The data for 3 soil column SAT and two field site are presented and discussed. Two Soil columns (0.3-4.0 m in depth) SAT were packed with silica sand and one soil column (2.75 m in depth) were packed with loamy sand. The concentration of trace organics such as EDTA, NTA, NDC and APEC fluctuates in the vadose zone, ie it increases and then reduces at certain depth below the recharge basin. This may be attributed to photo oxidation of EDTA during exposure to sunlight (Fox *et al.*, 2001b; Yoo *et al.*, 2006) or leaching of trace organics that were adsorbed during the previous flood. NTA is readily biodegradable, especially under aerobic conditions (Yoo *et al.*, 2006). NTA could be removed at relatively higher removal efficiency compared to NDC, EDTA and APEC all of which originated from the same SAT source water.

Most pharmaceuticals were removed to below detection; however antiepileptic drugs

such as carbamazepine and primidone persisted during SAT. The reason for this is unclear. Volatile organic compounds were reduced to very low concentration with excellent removals attributed to volatilization during recharge and biological transformation in the soil. EDCs that include estriol, estradiol and testosterone were also removed below detection via adsorption and bioactivity processes in the soil column. Effective contact time in SAT had higher influence on removal of EDCs under biotic-processes. The removal of EDC increased with contact time. Since EDCs have a high tendency to adsorb to porous media, adsorption is the primary mechanism for removal of EDC with degradation contributing to sustainable removal (Fox *et al.*, 2001b). Figures 4.22 and 4.23 show the performance of SAT systems in removing trace organics. The analysis of performance of SAT systems is shown on Tables 4.43 and 4.44 followed by guidelines (Tables 4.45 and 4.46) developed based on the analysis.

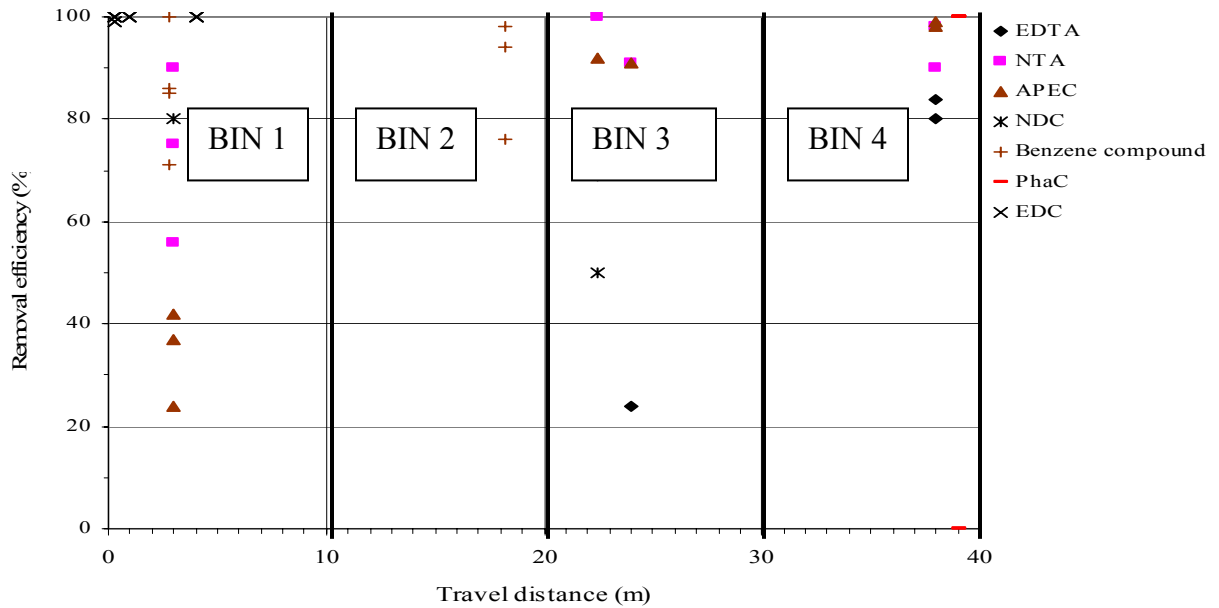


Figure 4.22 Trace organics removal efficiency vs. travel distance during soil aquifer treatment of secondary effluents

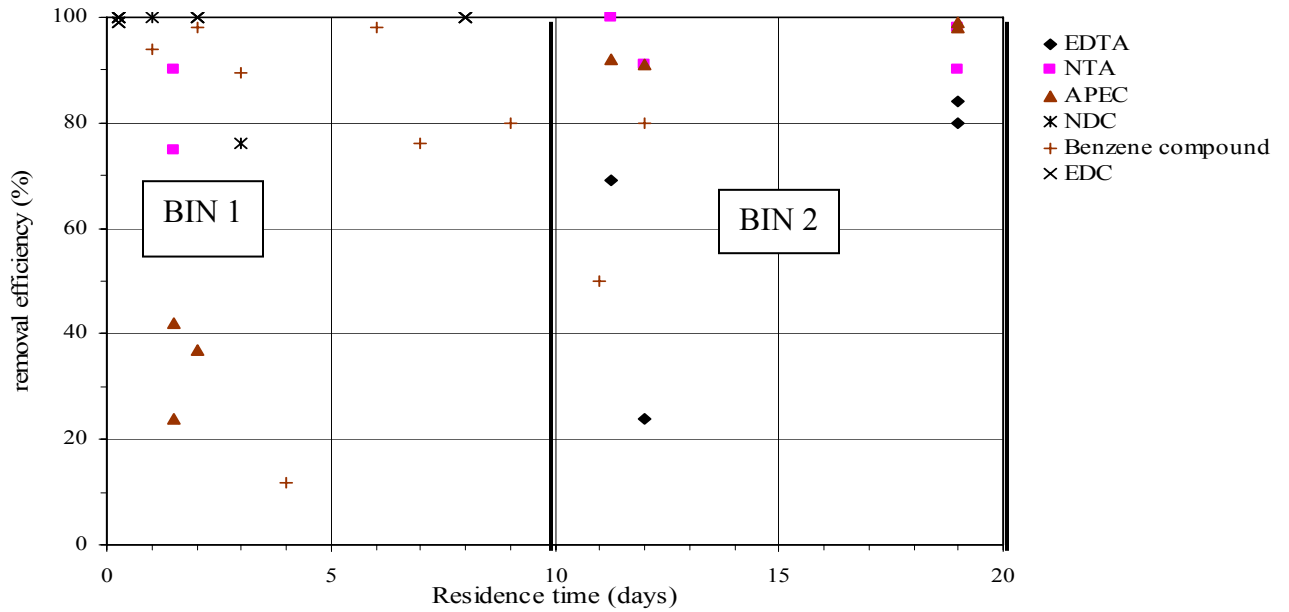


Figure 4.23 Trace organics removal efficiency vs. residence/travel time during soil aquifer treatment of secondary effluents

Table 4.43 Analysis of trace organics removal data for SAT systems treating secondary effluents at different travel distance

Trace organics	Travel distance (m)	Removal efficiency		Standard deviation (%)	No. of results
		Range	Average		
EDTA	20-30	24-69	47	32	2
	30-40	80-84	82	3	2
NTA	1-10	56-90	74	17	3
	20-30	91-100	96	6	2
	30-40	90-98	94	6	2
APEC	1-10	24-42	34	9	3
	20-30	91-92	92	1	2
	30-40	98-99	99	1	2
NDC	20-30	50-80	65	21	2
Benzene compound	10-20	76-98	89	12	3
PhaC	30-40	100-100	100	0	6
EDC	1-10	99-100	99.8	0.4	12

Table 4.44 Analysis of trace organics removal data for SAT systems treating secondary effluents at different residence/travel time

Trace organic	Residence/travel time	Removal efficiency		Standard deviation (%)	No. of results
		Range	Average		
EDTA	10-20	24-84	64	28	4
NTA	1-10	56-90	74	17	3
	10-20	90-100	95	5	4
APEC	1-10	24-42	34	9	3
	10-20	91-99	95	4	4
NDC	10-20	50-80	65	21	2
Benzene compounds	1-10	71-90	86	12	4
EDC	1-10	99-100	100	0.4	13
PhaCs	78	-	100	-	7

Based on the data analysis shown on Tables 4.43 and 4.44 and assuming that trace organic contribution is infiltrate from the recharge source only and the adsorption and biodegradation conditions are favourable for removal of trace organics, The guidelines for removal of trace organic are developed as shown in Tables 4.45 and 4.4.

Table 4.45 Guidelines for estimation of trace organics removal from secondary effluents during SAT with respect to travel distance

Trace organic	Influent quality (ng/L)	Travel distance (m)	Removal efficiency			Effluent quality (ng/L)
			Minimum	Average	Maximum	
EDTA	8000-34000	20-30	20	50	70	3000-26000
		30-40	80	80	80	
NTA	2000-6000	1-10	50	70	90	0-400
		20-30	90	96	100	
		30-40	90	>96	98	
APEC	40000-75000	1-10	20	30	40	1000-47000
		20-30	90	92	92	
		30-40	98	99	99	
NDC	2000-25000	20-30	50	60	80	1000-5000
Benzene compound	100-6000	10-20	70	80	98	10-120
PhACs	20-6000	30-40	100	100	100	0
EDCs	160-300	1-10	99	99.8	100	0-1.1

Note: Not all pharmaceuticals can be removed at such higher removal efficiency. The pharmaceutical removed at such a higher removal efficiency are Gemfibrozil, Diclofenac, Ibuprofen, Ketoprofen, Naproxen, Fenoprofen, and Propyphenazone

Table 4.46 Guidelines for estimation of trace organics removal from secondary effluents during SAT with respect to residence/travel time

Trace organic	Influent quality (ng/L)	Residence/travel time	Removal efficiency			Effluent quality (ng/L)
			Minimum	Average	Maximum	
EDTA	8000-34000	10-20	20	60	80	3000-5000
NTA	2000-5000	1-10	50	70	90	0-2000
		10-20	90	95	100	
APEC	40000-75000	1-10	20	30	40	600-47000
		10-20	90	95	99	
NDC	2000-25000	10-20	50	65	80	1000-5000
Benzene compounds	100-800	1-10	70	80	90	35-120
EDCs	161-200	1-10	99	100	0.4	0.4
PhACs	-	78	-	100	-	0

Note: Not all pharmaceuticals can be removed at such higher removal efficiency. The pharmaceutical removed at such a higher removal efficiency are Gemfibrozil, Diclofenac, Ibuprofen, Ketoprofen, Naproxen, Fenoprofen, and Propyphenazone

4.4.6 Microbe removal and guidelines for estimation of water quality

The performance of SAT system is explained in terms of removal efficiency of microbes that includes viruses and bacteria. Log removal represents the removal efficiency of microbes during SAT. The log used in this report is log 10 with 1log representing 90% removal efficiency, the other log removal with efficiencies in % shown in brackets are 2 log (99%), 3 log (99.9%), 4 log (99.99%), 5 log (99.999%) etc; higher log removal implies higher number of microbes were removed. Different SAT systems give different results depending on microbial activity, size of soil particles, size of microbes, and ability of microbes to persist in soil (Powelson *et al.*, 1993; Quanrud *et al.*, 2003b; Rice and Bouwer, 1984). If one system can be assessed separately the general trend expected is that the removal of microbes increases with travel distance. Much better removal is expected on the larger size microbes.

The data for soil column and four site SAT are presented and discussed in this section. Two SAT site are located in Yavne and Soreq in Israel and the other two in Phoenix and Tucson in Arizona, USA. Columns SAT were packed with limey sand (1), sandy loam (1), sandy lime (1), silica sand (1) and poorly graded sand (1). During SAT of secondary effluents some SAT system demonstrated excellent removal of bacteria of fecal pollution to beyond detection level. Other SAT systems removed bacteria to very low concentration in SAT product water as compared to effluent quality recharged. Virus removal is more efficient in finer grained soils (Quanrud *et al.*, 2003b). The performance of SAT is presented in Figures 4.24 and 4.26. Figure 4.25 shows the 5, 25, 75, 95 percentile and median of data used to develop the guidelines for ammonia removal during

SAT. The analysis of performance of SAT systems is shown on Tables 4.47 and 4.48 followed by guidelines developed on the basis of this analysis.

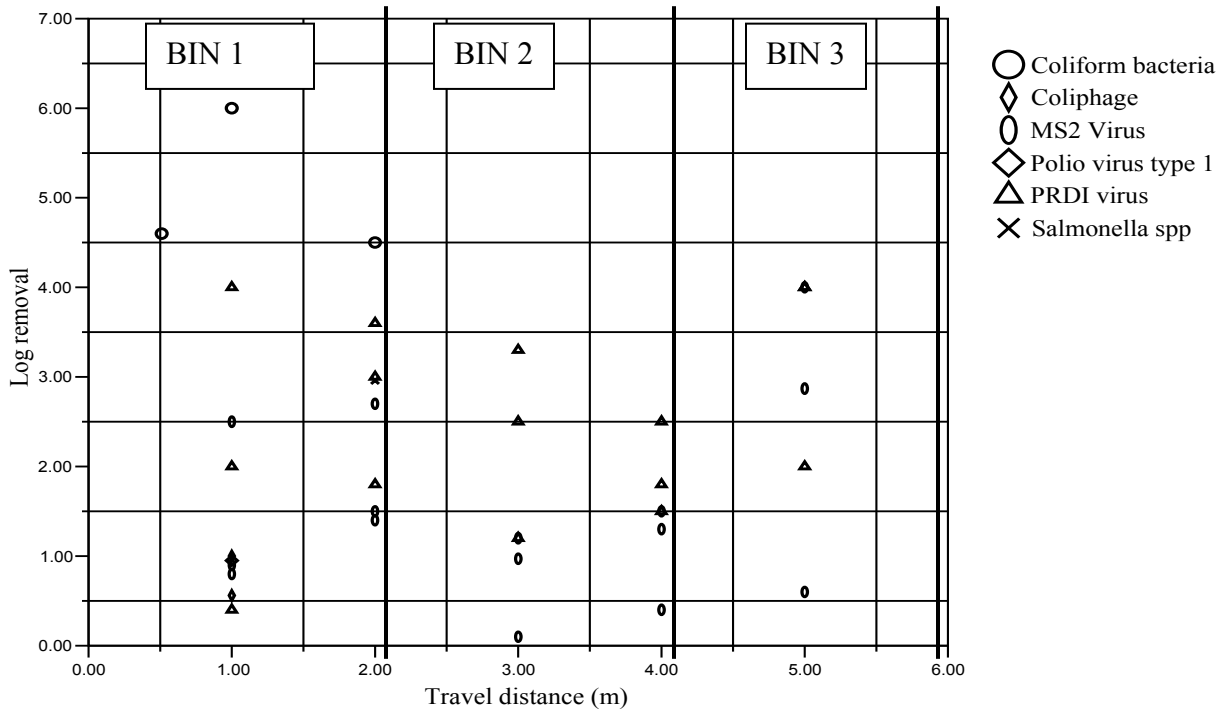


Figure 4.24 Microbe removal efficiency vs. travel distance during soil aquifer treatment of secondary effluents

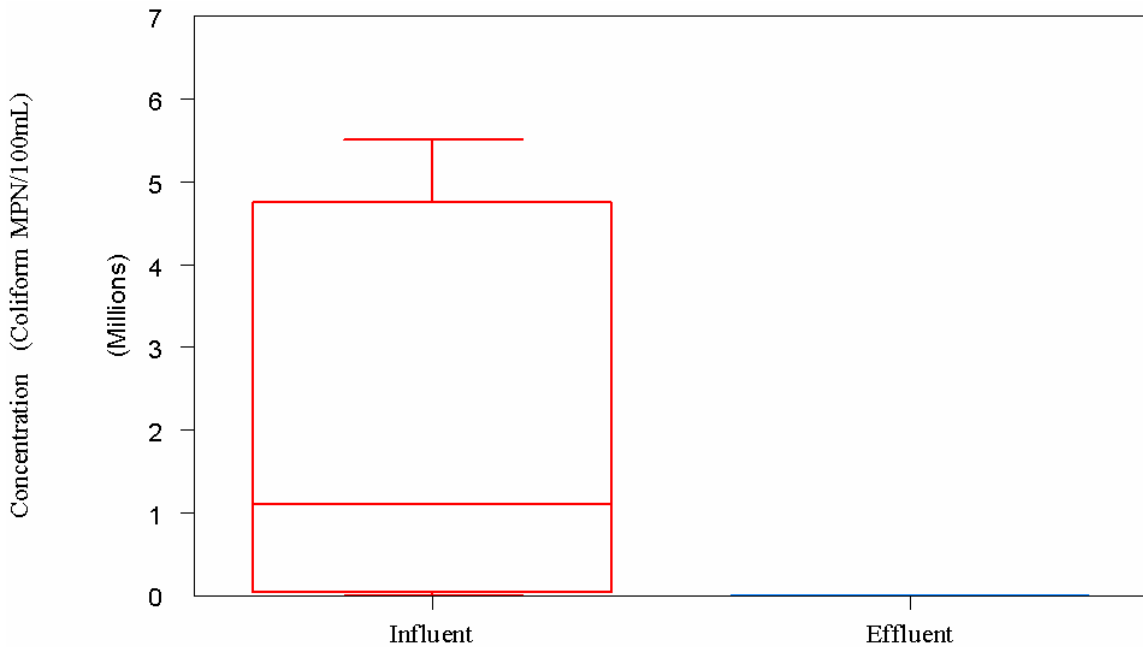


Figure 4.25 Box and Whisker graph for data used in guidelines for bacteria removal with respect to travel distance and travel time during soil aquifer treatment of secondary effluents

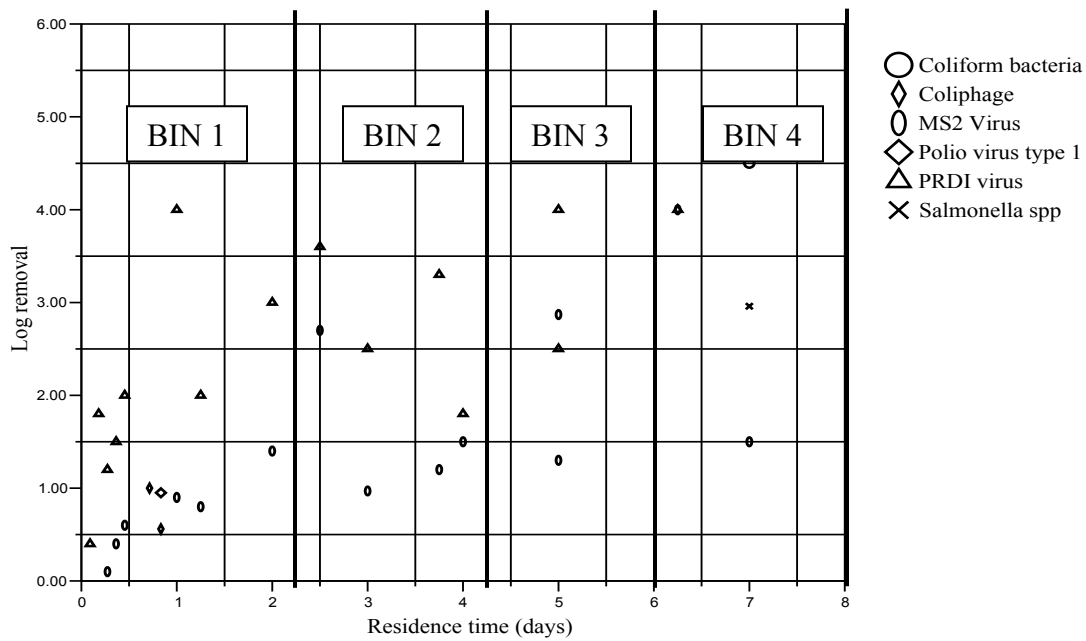


Figure 4.26 Microbe removal efficiency vs. residence/travel time during soil aquifer treatment of secondary effluents

Table 4.47 Analysis of microbe removal data for SAT systems treating secondary effluents at different travel distance

Microbe	Travel Distance (m)	Log removal		Standard deviation (log removal)	No. of results
		Range	Average		
Virus	1-2	0.4-4	2	1	15
	2-4	0.1-3	2	1.2	12
	4-6	0.6-4	3	1	6
Coiliform and Salmonella spp	1-2	1-6	4	2	5
	>2	2-6	4	2	6

Table 4.48 Analysis of microbe removal data for SAT systems treating secondary effluents at different residence/travel time

Microbe	Residence/travel time(days)	Log removal		Standard deviation (log)	No. of results
		Range	Average		
Virus	0.5-2	0.1-5	2	1	18
	2-4	1-4	2	1	8
	4-6	1-4	3	1	4
	6-8	2-4	3	1	3
Coiliform and Salmonella spp	6-8	1-5	3	2	3
	>8	2-6	4	2	7

Based on the data analysis shown in Tables 4.47 and 4.48 above and assuming that the

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contribution of microbes is via infiltrate from the recharge source only, and the conditions allow microbes removal, the guidelines for removal of microbe are developed as shown in Tables 4.49 and 4.50.

Table 4.49 Guidelines for estimation of microbe removal from secondary effluents during SAT with respect to travel distance

Microbe	Travel Distance (m)	Log removal		
		Minimum	Average	Maximum
Virus	1-2	0.4	2	3
	2-4	0.1	2	3
	4-6	0.6	3	4
	>6	>0.6	>3	>4
Coiliform and Salmonella spp	1-2	1	4	6
	>2	>1	>4	>6

Table 4.50 Guidelines for estimation of microbe removal from secondary effluents during SAT with respect to residence/travel time

Microbe	Travel time (days)	Log removal		
		Minimum	Average	Maximum
Virus	0.5-2	0.1	2	5
	2-4	1	2	4
	4-6	1	3	4
	>6	>1	>3	>4
Coiliform and Salmonella spp	6-8	1	3	5
	>8	>1	>4	>5

Table 4.51 Summary: Guidelines for estimation of removal of contaminants from secondary effluents during SAT with respect to residence/travel time

Contaminants	Influent quality (mg/L)	Travel Distance (m)	Removal efficiency (%)			Effluent quality (mg/L)	
			Minimum	Average	Maximum		
DOC	4-15	1-5	15	50	70	1.5-10	
		5-25	70	80	90		
		>25	>70	>80	>90		
	Influent quality (mg/L)	2-24	Residence/travel time (days)	Removal efficiency (%)			Effluent quality (mg/L)
				Minimum	Average	Maximum	
			1-10	10	50	70	
			10-30	20	60	90	
			30-50	70	80	90	
	>50	>70	>80	>90			
NH ₄ -N	Influent quality (mg/L)	Travel distance (m)	Removal efficiency (%)			Effluent quality (mg/L)	
				Minimum	Average		Maximum
			5-60	0.3-1.0	20		70
		1.0-2.5	50	80	99		
		>2.5	>50	>80	>99		
	Influent quality (mg/L)	5-60	Residence/travel time (days)	Removal efficiency (%)			Effluent quality (mg/L)
				Minimum	Average	Maximum	
			1-5	20	60	99	
5-25			70	90	>99		
>25			>70	>90	>99		
NO ₃ -N	Influent quality (mg/L)	Travel distance (m)	Removal efficiency (%)			Effluent quality (mg/L)	
				Minimum	Average		Maximum
			3.5-30.0	1-5	3		60
		>5	>3	>60	>90		
	Influent quality (mg/L)	Residence/Travel time (days)	Removal efficiency (%)			Effluent quality (mg/L)	
				Minimum	Average		Maximum
1-10			3	60	90		
>10			>3	>60	>90		
	>30	10	>40	>40			
PO ₄ -P	Influent quality (mg/L)	Travel distance (m)	Removal efficiency (%)			Effluent quality (mg/L)	
				Minimum	Average		Maximum
			2-12	1-500	60		80
		>500	99	99	>99		
	Influent quality (mg/L)	Travel time (days)	Removal efficiency (%)			Effluent quality (mg/L)	
				Minimum	Average		Maximum
2-12			1-100	60	80		99
	>100	99	99	>99			

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Summary table: Guideline for estimation of contaminants removal from secondary effluents during SAT with respect to residence/travel time-continue

Trace organics	Influent quality (ng/L)	Travel distance (m)	Removal efficiency			Effluent quality (ng/L)
			Minimum	Average	Maximum	
EDTA	8000-34000	20-30	20	50	70	3000-26000
		30-40	80	80	80	
NTA	2000-6000	1-10	50	70	90	0-400
		20-30	90	96	100	
		30-40	90	>96	98	
APEC	40000-75000	1-10	20	30	40	1000-47000
		20-30	90	92	92	
		30-40	98	99	99	
NDC	2000-25000	20-30	50	60	80	1000-5000
Benzene compound	100-6000	10-20	70	80	98	10-120
PhACs	20-6000	30-40	100	100	100	0
EDCs	160-300	1-10	99	99.8	100	0-1.1
Trace organics	Influent quality (ng/L)	Residence/travel time	Removal efficiency			Effluent quality (ng/L)
			Minimum	Average	Maximum	
EDTA	8000-34000	10-20	20	60	80	3000-5000
NTA	2000-5000	1-10	50	70	90	0-2000
		10-20	90	95	100	
APEC	40000-75000	1-10	20	30	40	600-47000
		10-20	90	95	99	
NDC	2000-25000	10-20	50	65	80	1000-5000
Benzene compounds	100-800	1-10	70	80	90	35-120
EDCs	161-200	1-10	99	100	0.4	0.4
PhACs		78	-	100	-	0
Microbes	Travel Distance (m)	Log removal				
		Minimum	Average	Maximum		
Virus		1-2	0.4	2	3	
		2-4	0.1	2	3	
		4-6	0.6	3	4	
		>6	>0.6	>3	>4	
Coiliform and Salmonela spp		1-2	1	4	6	
		>2	>1	>4	>6	
Virus	Residence/travel time (days)	Log removal				
		Minimum	Average	Maximum		
		0.5-2	0.1	2	5	
		2-4	1	2	4	
		4-6	1	3	4	
		>6	>1	>3	>4	
Coiliform and Salmonela spp		6-8	1	3	5	
		>8	>1	>4	>5	

It is to be noted that while making a quick assessment of the SAT system using these guidelines, the guideline for microbe removal which is most crucial should be given a priority. However other guidelines should be applied according to needs. It is recommended to choose maximum distances stated in the guidelines in order to reduce risks of pumping water which is not sufficiently treated during SAT.

4.5 Attenuation of contaminants from tertiary effluents and guidelines development

4.5.1 DOC removal and guideline for estimation of water quality

Field and laboratory-scale SAT data which include eight soil columns and three batch experiments are presented and discussed in this section. The SAT sites are located in Germany with one site in Berlin, China with one site in Beijing and one site in Mesa, Arizona in USA. Mesa and Berlin field sites received chlorinated effluents. Soil columns (1-2 m in depth) were packed with quartz sand (1), loamy sand (1) and sand-grain size 1-2 mm (5). Batch reactors contained sandy soil only. The site SAT systems consisted of surface spread basins with vadose zone depth ranging from 19 to 50m and recovery wells located approximately 400 m and 900 m down gradient from surface spread basins. The travel/residence times ranged from approximately 1 day to 30 and 1day to more than 18 months in laboratory scale and site scale SAT respectively.

The general trend on DOC removal during SAT showed an increase with a travel distance and a residence/travel time. DOC concentration of SAT product water was <2 mg/L which is below the average DOC found in drinking water supply which is 2.2 mg/L (Amy and Drewes, 2006a; Fox *et al.*, 2001a; Jarusutthirak *et al.*, 2003). Figures 4.24 and 4.25 show the performance of SAT with respect to different distances and residence/travel times respectively. Like SAT of secondary effluent, DOC is mostly removed within a travel distance of 5m (bin 1) approximately 16%-73% which is comparable DOC removal in soil aquifer treatment of secondary effluent within the same distance (Figure 4.9). DOC concentration significantly decreased within the top 2m of site SAT. Apparent decrease in DOC removal in bin 3 in Figures 4.27 may be the influence of DOC from other sources or leaching of DOC from soil. The analysis of DOC removal data is shown on Tables 4.52 and 4.53 and the guidelines for DOC estimation on Tables 4.54 and 4.55.

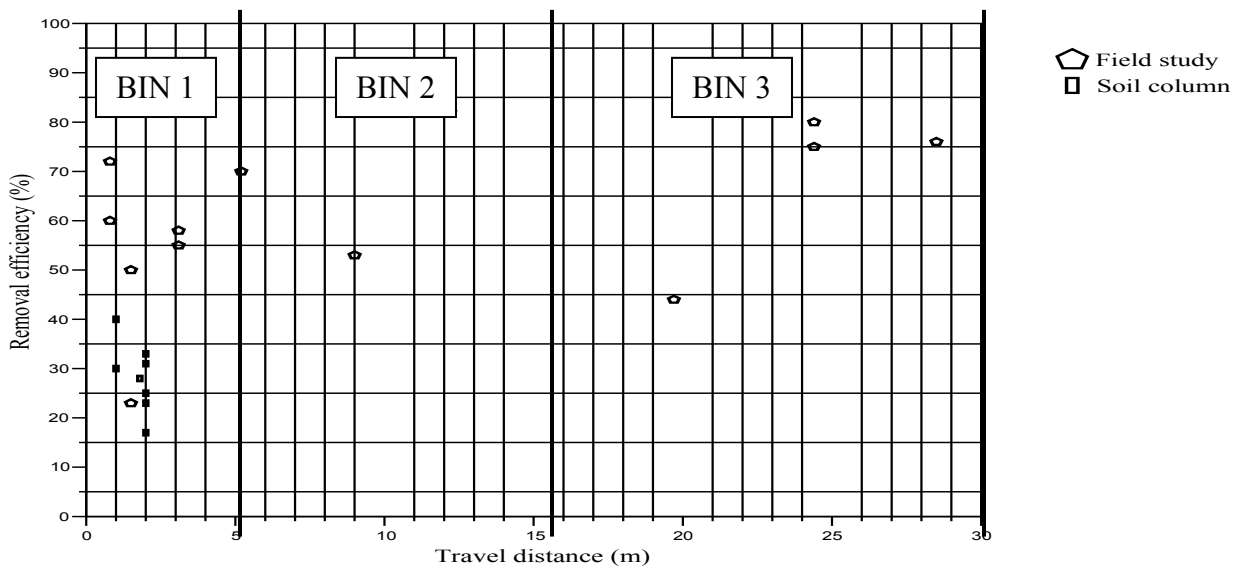


Figure 4.27 DOC removal efficiency vs. travel distance during soil aquifer treatment of tertiary effluents

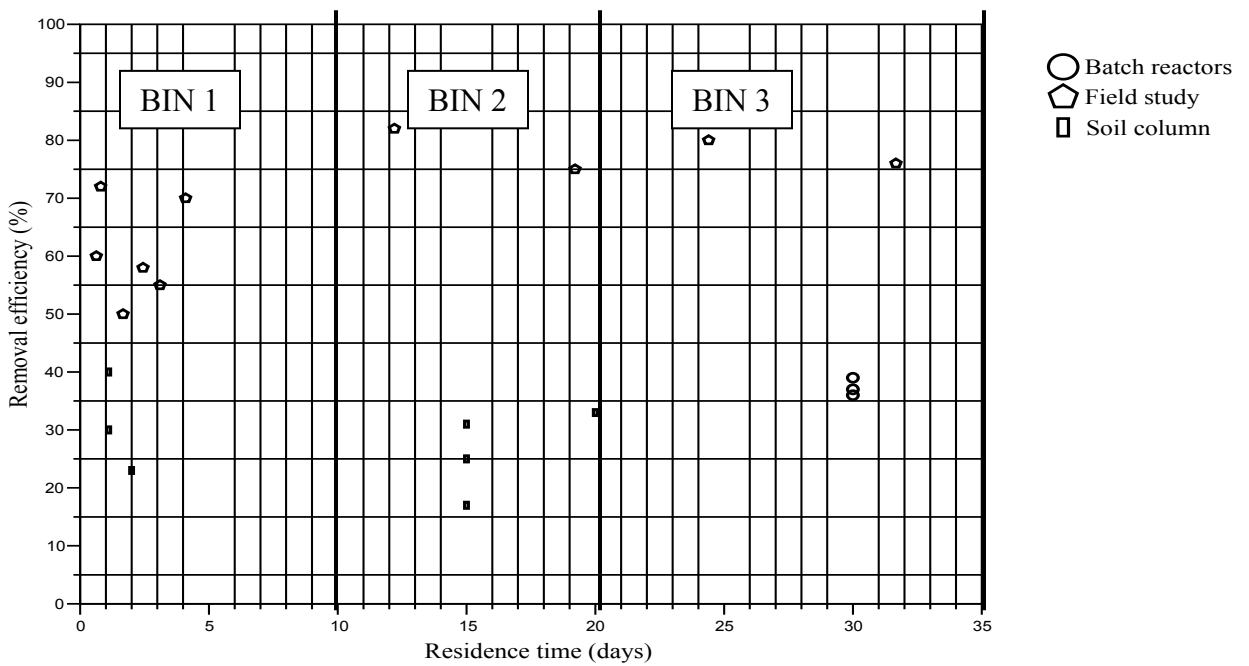


Figure 4.28 DOC removal efficiency vs. residence/travel time during soil aquifer treatment of tertiary effluents

Table 4.52 Analysis of DOC removal data for SAT systems treating tertiary effluents at different travel distance

Travel Distance (m)	Removal efficiency (%)		Standard deviation (%)	No. of results
	Range	Average		
1-5	19-72	39	17	14
5-15	53-82	68	15	3
>15	40-80	72	12	4

Table 4.53 Analysis of DOC removal data for SAT systems treating tertiary effluents at different residence/travel time

Residence/travel time (days)	Removal efficiency (%)		Standard deviation (%)	No. of results
	Range	Average		
1-10	23-72	48	18	9
10-20	17-82	45	25	6
>20	28-80	59	21	10

Based on data analysis above and, assuming that DOC contribution for SAT system is derived from infiltrates from recharge source only, and redox and biomass conditions are sufficient to influence DOC removal, and in general under the normal operating condition DOC removal increases with travel distance and residence/travel time, guidelines for estimation of DOC removal with respect to travel distance and travel/residence time are developed as shown in Tables 4.54 and 4.55 respectively

Table 4.54 Guidelines for estimation of DOC removal from tertiary effluents during SAT with respect to travel distance

Influent quality (mg/L)	Travel distance (m)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
5-20	1-5	20	40	70	2-14
	5-15	50	70	80	
	>15	>50	>70	>80	

Table 4.55 Guidelines for estimation of DOC removal from tertiary effluents during SAT with respect to residence/travel time

Influent quality (mg/L)	Residence/travel time (days)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
5-24	1-10	20	50	70	2-14
	10-20	25	50	80	
	>20	>25	>50	>80	

4.5.2 NH₄-N removal and guideline for prediction of water quality

Data from two SAT and one soil column studies (1.2 m in depth) packed with quartz sand are plotted as shown in Figures 4.29 and 4.30. One field SAT is located in Berlin, German and another one in Sulaibaya, Kuwait. Like in treatment sites of secondary

effluents ammonia was mostly removed in the top 1.5 m soil of field site SAT. Ammonia was completely removed in Sulaibaya SAT site, indicating highly aerobic condition (Viswanathan *et al.*, 1999). Ammonia is converted nitrate during SAT which may lead to increased nitrate concentration in groundwater (Reemtsma *et al.*, 2000; Viswanathan *et al.*, 1999). The analysis of ammonia nitrogen removal is shown on Tables 4.56 and 4.57 followed by guidelines developed based on the analysis.

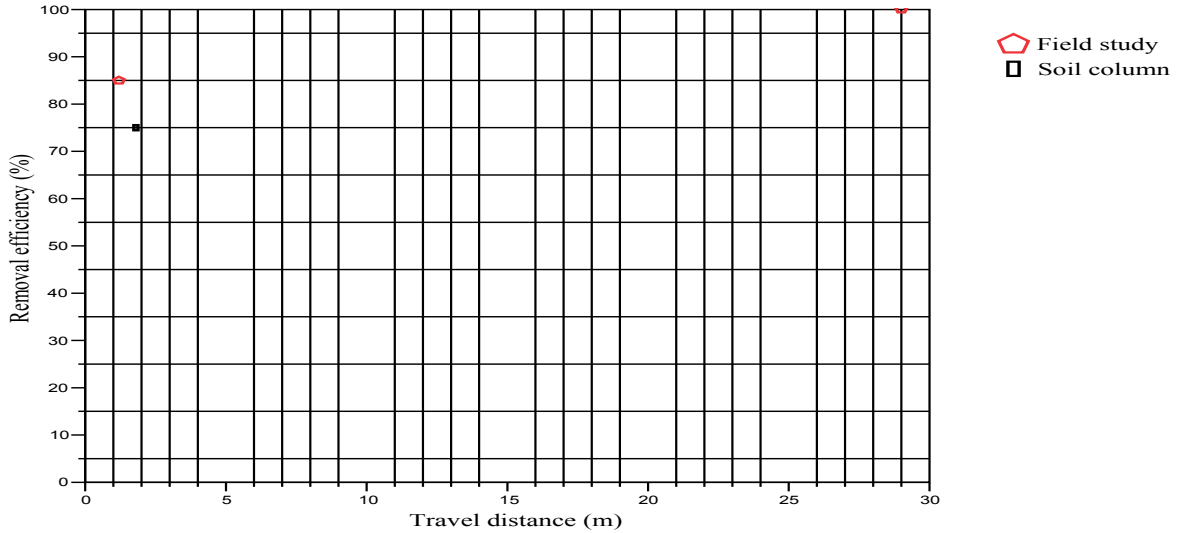


Figure 4.29 NH₄-N removal efficiency vs. travel distance during soil aquifer treatment of tertiary effluents

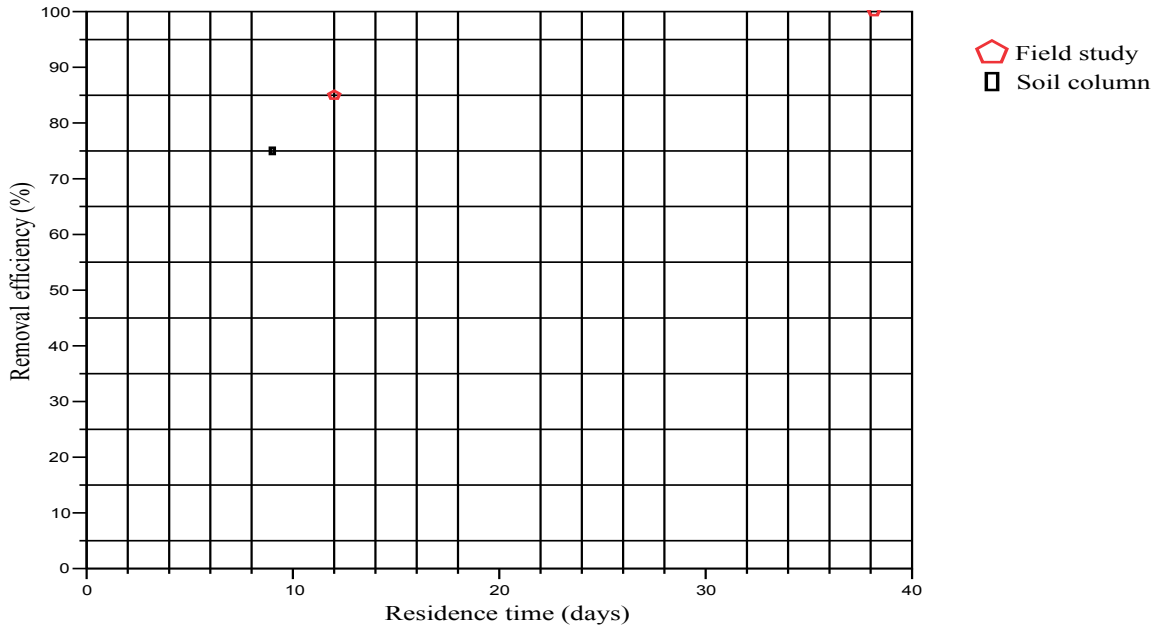


Figure 4.30 NH₄-N removal efficiency vs. residence/travel time during soil aquifer treatment of tertiary effluents

Table 4.56 Analysis of NH₄-N removal data for SAT systems treating tertiary effluents at different travel distances

Travel distance (m)	Removal efficiency (%)		Standard deviation (%)	No. of results
	Range	Average		
1-2	75-85	80	-	2

Table 4.57 Analysis of NH₄-N removal data for SAT systems treating tertiary effluents at different residence/travel times

Residence/Travel time (days)	Removal efficiency (%)		Standard deviation (%)	No. of results
	Range	Average		
1-20	75-85	80	-	2

Based on data analysis above assuming that ammonia contribution for SAT system is infiltrates from recharge source only and in general under the normal operating condition ammonia removal increases with travel distance and residence/travel time, guidelines for estimation of ammonia removal with respect to travel distance and travel/residence time are developed as shown in Tables 4.58 and 4.59 respectively.

Table 4.58 Guidelines for estimation of NH₄-N removal from tertiary effluents during SAT with respect to distance

Influent quality (mg/L)	Travel distance (m)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
1.5-2.0	1-2	75	80	85	0.2-0.5
	>	>75	>80	>85	

Table 4.59 Guidelines for estimation of NH₄-N removal from tertiary effluents during SAT with respect to residence/travel time

Influent quality (mg/L)	Residence/Travel time (days)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
1.5-2.0	1-20	75	80	85	0.2-0.5
	>	>75	>80	>85	

4.5.3 NO₃-N removal and guideline for prediction of water quality

SAT data for nitrate removal during SAT which are presented and discussed in this section includes data from one simulated SAT soil column (1.8 m in depth) and two SAT site. The soil column SAT was packed with quartz sand. One field SAT is located in Berlin, German and another one in Sulaibaya, Kuwait. During SAT nitrate was removed by partial denitrification under anoxic conditions during the vertical flow in the vadose zone. In the Sulaibaya site SAT nitrate removal was 21% which indicates limited anoxic conditions (Viswanathan *et al.*, 1999). In the Berlin SAT there was no denitrification, therefore nitrate was released from the soil leading to an increase in nitrate concentration in groundwater (Reemtsma *et al.*, 2000). Figures 4.31 and 4.32 show the performance of SAT systems removing and producing nitrate with respect to travel distance and

residence/travel time respectively. Due to limitation of data the guideline for nitrate removal from tertiary effluent is not developed.

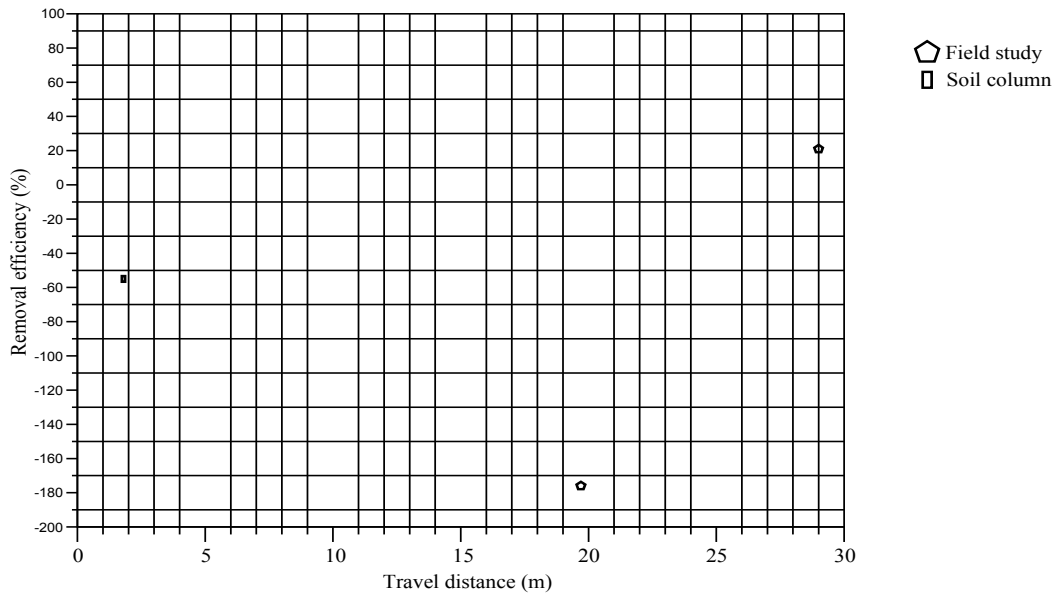


Figure 4.31 NO₃-N removal efficiency vs. travel distance during soil aquifer treatment of tertiary effluents

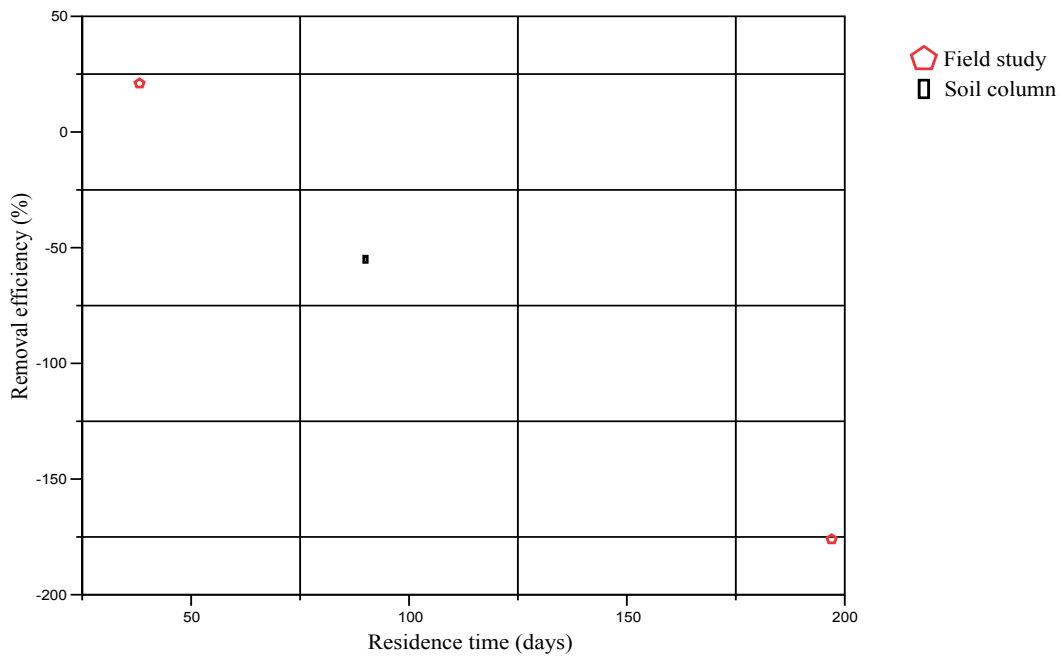


Figure 4.32 NO₃-N removal efficiency vs. travel distance during soil aquifer treatment of tertiary effluents

4.5.4 PO₄-P removal and guideline for estimation of water quality

Results for two SAT site and one soil column (1.8 m in depth) are presented and discussed in this section. One field SAT is located in Berlin, German and another one in Sulaibaya, Kuwait. The soil column used in simulating SAT was field with quartz sand removed 37% of phosphorus from the influent. SAT site in Berlin leached phosphorus 12 times the influent concentration at travel distance of about 20 m. SAT site soils in Berlin was saturated with phosphate leading to the release into percolating water (Reemtsma *et al.*, 2000). SAT site in Sulaibaya removed 80% of phosphorus from tertiary effluent. Recovered water is used for unrestricted irrigation of agricultural crops; therefore there is no need to reduce the phosphorus load in SAT product water. Where potable reuse is needed then phosphorus load in SAT product water has to be significantly reduced. The performance of SAT systems is shown on Figures 4.33 and 4.34 and the analysis phosphorus removal data are shown on Tables 4.60 and 4.61 followed by guidelines in Tables 4.62 and 4.63.

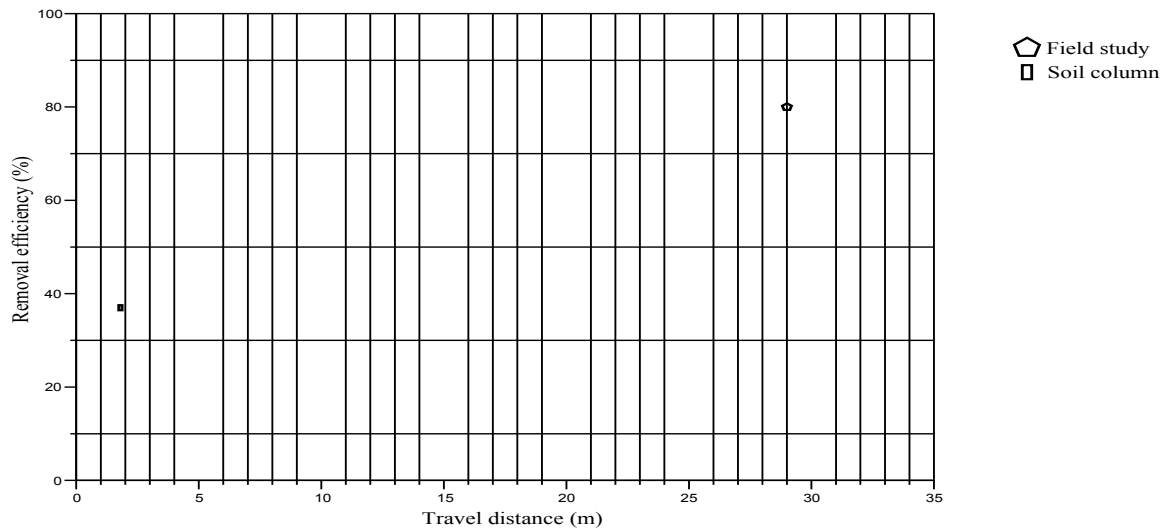


Figure 4.33 PO₄-P removal efficiency vs. travel distance during soil aquifer treatment of tertiary effluents

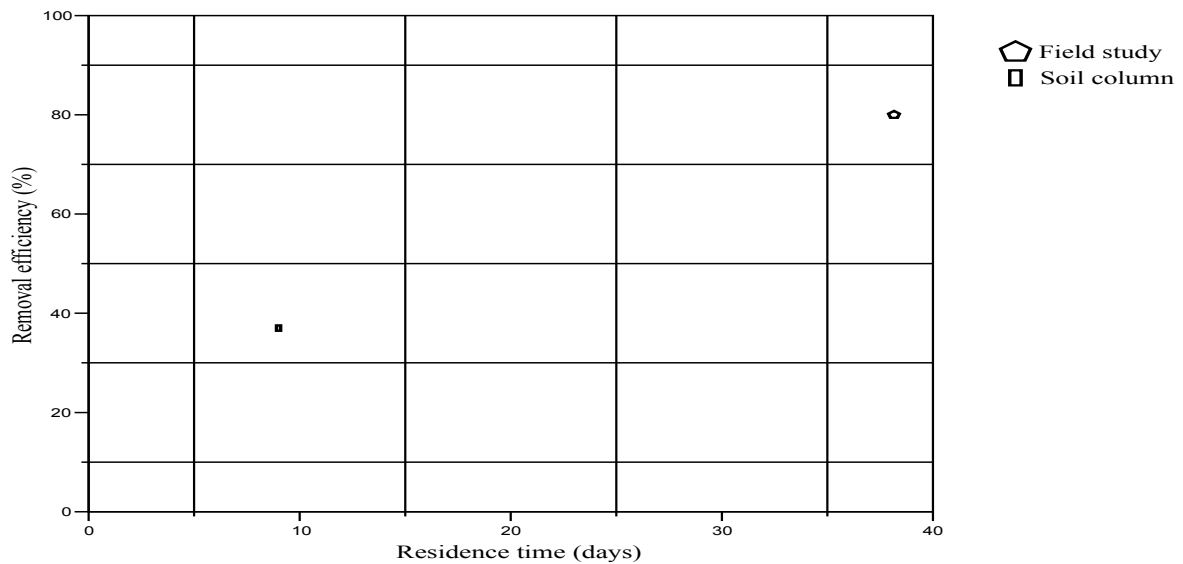


Figure 4.34 PO₄-P removal efficiency vs. residence/travel time during soil aquifer treatment of tertiary effluents

Table 4.60 Analysis of PO₄-P removal data for SAT systems treating tertiary effluents at different travel distance

Travel distance (m)	Removal efficiency (%)		Standard deviation (%)	No. of results
	Range	Average		
1-30	37-80	59	30	2

Table 4.61 Analysis of PO₄-P removal data for SAT systems treating tertiary effluents at different residence/travel times

Residence/Travel time (days)	Removal efficiency (%)		Standard deviation (%)	No. of results
	Range	Average		
5-40	37-59	59	30	2

Based on the data analysis shown on table 4.60 and table 4.61 above and assuming that PO₄-P contribution is infiltrate from the recharge source only and that adsorbed PO₄-P break through is not expected the guideline was developed as shown in Tables 4.62 and 4.63.

Table 4.62 Guidelines for estimation of PO₄-P removal from tertiary effluents during SAT with respect to distance

Influent quality (mg/L)	Travel distance (m)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
0.2-16.0	1-30	40	60	80	0.1-3.3
	>30	>40	>60	>80	

Table 4.63 Guidelines for estimation of PO₄-P removal from tertiary effluents during SAT with respect to residence/travel time

Influent quality (mg/L)	Residence/Travel time (days)	Removal efficiency (%)			Effluent quality (mg/L)
		Minimum	Average	Maximum	
0.2-16.0	5-40	40	60	80	0.1-3.3
	>40	>40	>60	>80	

4.5.5 Trace organics removal and guideline for estimation of water quality

The trace organics discussed in this section are EDTA, NTA, NDC, APEC, EDC and Pharmaceuticals (Carbamazepine and Primidone). Only one site SAT data are presented and discussed in this section, the site SAT is located in Mesa, Arizona in USA. Pharmaceuticals are lesser removed than other trace organics. These pharmaceuticals persisted during SAT of secondary effluent (section 4.4.5) this shows that no contaminant is completely persistent to SAT. NTA was 100% removed during SAT, this is because it is readily biodegradable (Yoo *et al.*, 2006). The performance of SAT systems is shown on Figures 4.35 and 4.36. The analysis of performance of SAT systems is shown on Tables 4.64 and 4.65 followed by guidelines developed on the basis of the data analysis.

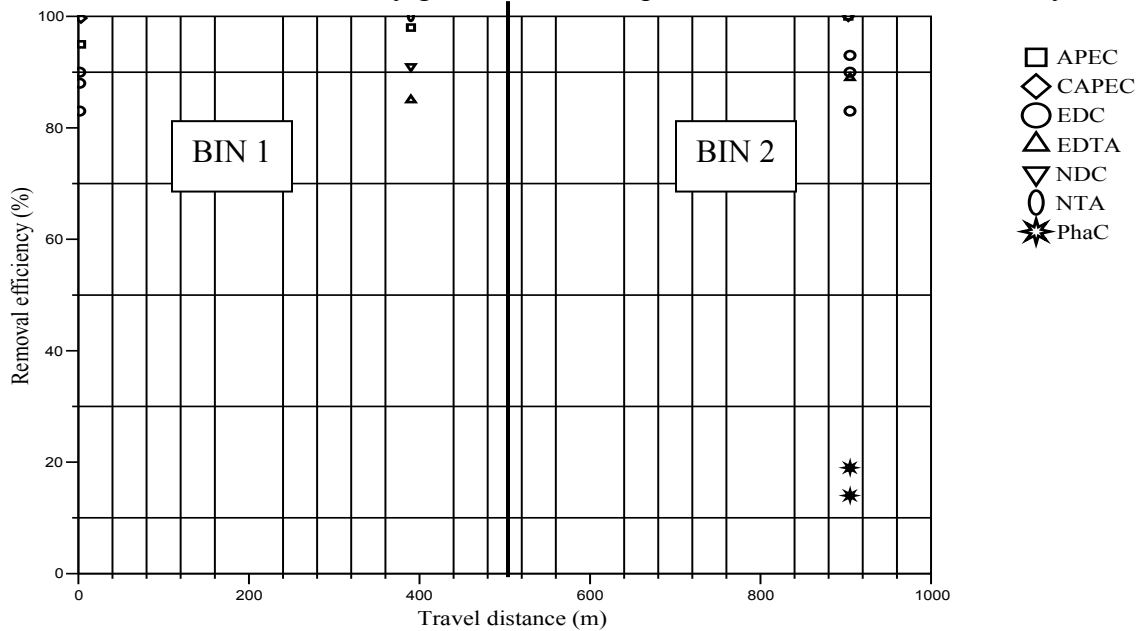


Figure 4.35 Trace organics removal efficiency vs. travel distance during soil aquifer treatment of tertiary effluents

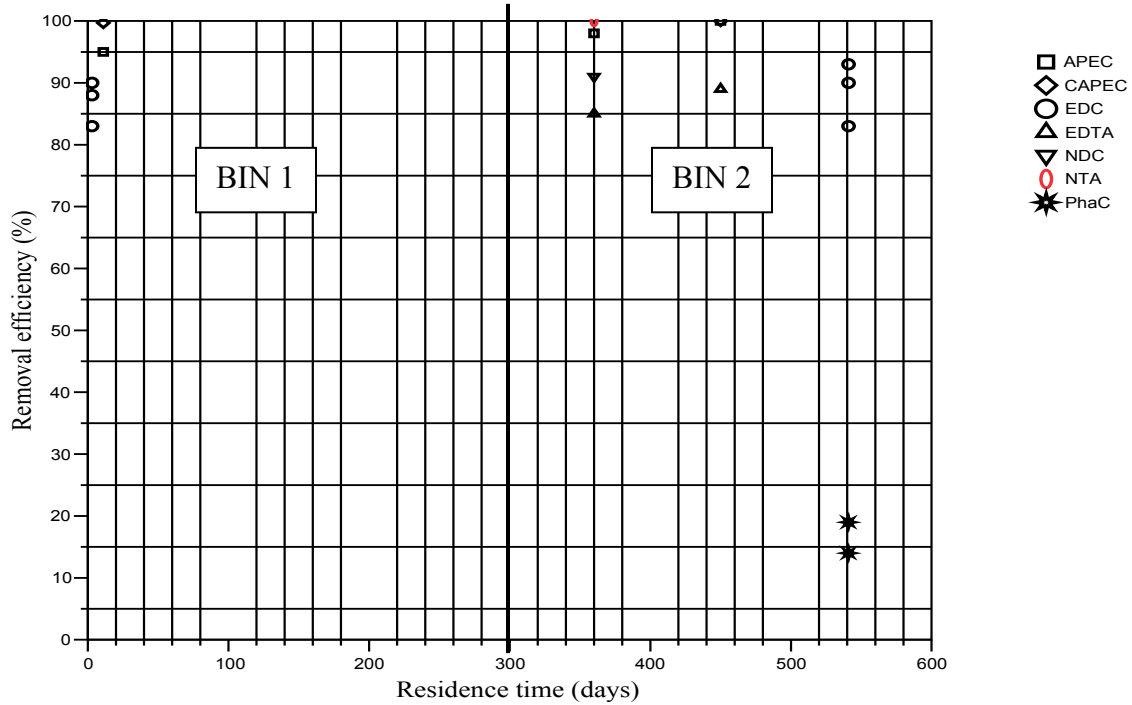


Figure 4.36 Trace organics removal efficiency vs. residence/travel time during soil aquifer treatment of tertiary effluents

Table 4.64 Analysis of trace organics removal data for SAT systems treating tertiary effluents at different travel distance

Trace organics	Travel distance(m)	Removal efficiency		Standard deviation (%)	No. of results
		Range	Average		
EDTA, NTA, NDC, APEC, CAPEC, NDC, EDC	1-500	83-100	92	6	9
	500-1000	83-100	94	7	5
PhACs	500-1000	14-19	17	19	2

Table 4.65 Analysis of trace organic removal Data for SAT systems treating tertiary effluents at different residence/travel time

Trace organics	Residence/Travel time(days)	Removal efficiency		Standard deviation (%)	No. of results
		Range	Average		
EDTA, NTA, NDC, APEC, CAPEC, NDC, EDC	1-300	83-99	91	6	5
	300-600	83-100	94	6	9
PhACs	300-600	14-19	17	19	2

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Based on the data analysis shown on Tables 4.64 and 4.65 above and assuming that trace organic is via contribution of infiltrate from the recharge source only. The guidelines for removal of trace organic are developed as shown in table 4.66 and table 4.67.

Table 4.66 Guidelines for estimation of trace organics removal from tertiary effluents during SAT with respect to travel distance

Trace organics	Travel distance (m)	Removal efficiency		
		Minimum	Average	Maximum
EDTA, NTA, NDC, APEC, CAPEC, NDC, EDC	1-500	80	90	100
	500-1000	80	90	100
	>1000	>80	>90	100
PhACs	500-1000	10	17	20
	>1000	>10	>17	>20

Table 4.67 Guidelines for estimation of trace organic removal from tertiary effluents during SAT with respect to residence/travel time

Trace organic	Residence/Travel time(days)	Removal efficiency		
		Minimum	Average	Maximum
EDTA, NTA, NDC, APEC, CAPEC, NDC, EDC	1-300	80	90	100
	300-600	80	90	100
	>600	>80	>90	100
PhACs	300-600	10	17	20
	>600	>10	>17	>20

4.5.6 Microbe removal and guideline for estimation of water quality

The data for two SAT site only are presented and discussed in this section. SAT site are located in Arizona, USA and Sulaibaya in Kuwait. During SAT of tertiary effluents Sulaibaya SAT system demonstrated excellent removal of faecal coliform (results not shown in Figures 4.37 and 4.38) to below detection level. Arizona SAT removed virus that generally increased with travel time and distance. MS2 and PRDI which was removed during SAT has low adsorption to soil and survive long to the environment (Powelson *et al.*, 1993). Performance of SAT is presented in Figures 4.33 and 4.34. The analysis of performance of SAT systems is shown on Tables 4.68 and 4.69 followed by

guidelines developed on the basis of the analysis.

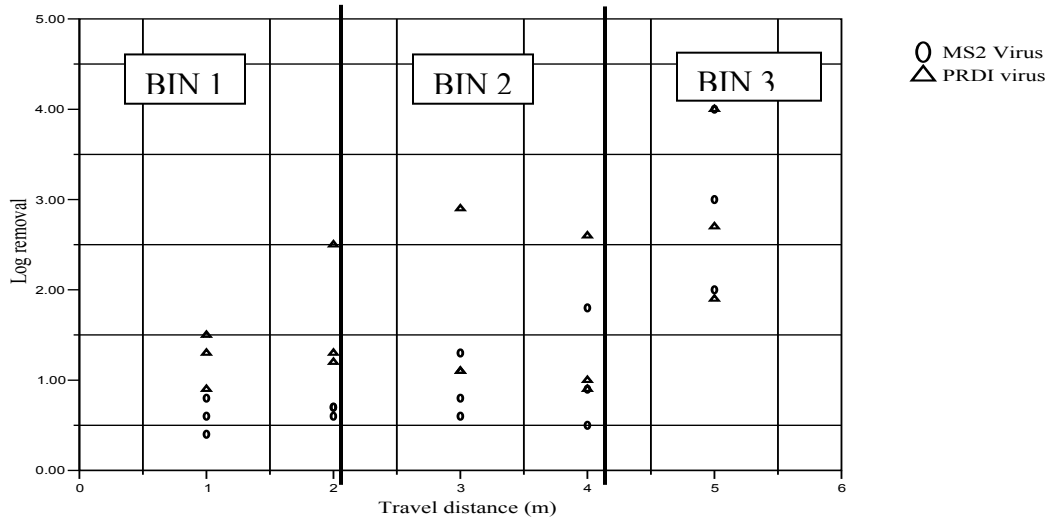


Figure 4.37 Microbe removal efficiency vs. travel distance during soil aquifer treatment of tertiary effluents

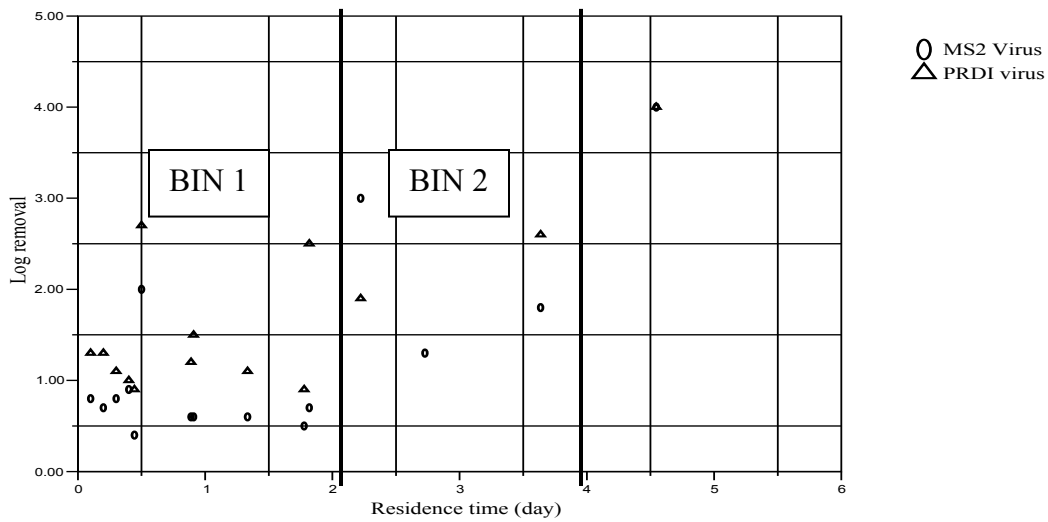


Figure 4.38 Microbe removal efficiency vs. residence/travel time during soil aquifer treatment of tertiary effluents

Table 4.68 Analysis of microbe removal data for SAT systems treating tertiary effluents at different travel distance

Microbe	Travel distance (m)	Log removal		Standard deviation (log)	No. of results
		Range	Average		
Virus	1-2	0.4-2.5	1.0	0.6	12
	2-4	0.5-2.9	1.3	0.8	12
	4-6	1.9-4	2.9	0.9	6

Table 4.69 Analysis of microbe removal data for SAT systems treating tertiary effluents at different residence/travel time

Microbe	Residence/Travel time(days)	Log removal		Standard deviation (log)	No. of results
		Range	Average		
Virus	1-2	0.4-2.7	1.1	0.6	22
	2-4	1.3-3.0	2.3	0.7	6
	4-6	-	4	0	2

Based on the data analysis shown in Tables 4.68 and 4.69 above and assuming that the contribution of microbes is via infiltrate from the recharge source only, and the conditions allow microbes removal, the guidelines for removal of microbe are developed as shown in Tables 4.70 and 4.71.

Table 4.70 Guidelines for estimation of microbe removal from tertiary effluents during SAT with respect to travel distance

Microbe	Travel distance (m)	Log removal		
		Minimum	Average	Maximum
Virus	1-2	0.4	1.0	2.5
	2-4	0.5	1.3	2.9
	4-6	1.9	2.9	4
	>6	>1.9	>2.9	>4

Table 4.71 Guidelines for estimation of microbe removal from tertiary effluents during SAT with respect to residence/ travel time

Microbe	Residence/Travel time(days)	Log removal		
		Minimum	Average	Maximum
Virus	1-2	0.4	1.1	2.7
	2-4	0.5	2.3	3.0
	>4	1.9	>2.3	>3

Table 4.72 Summary: guidelines for estimation of contaminants removal from tertiary effluents during SAT with respect to travel distance and travel time

Contaminant	Influent quality (mg/L)	Travel distance (m)	Removal efficiency (%)			Effluent quality (mg/L)
			Minimum	Average	Maximum	
DOC	5-20	1-5	20	40	70	2-14
		5-15	50	70	80	
		>15	>50	>70	>80	
	Influent quality (mg/L)	Residence/ travel time (days)	Removal efficiency (%)			Effluent quality (mg/L)
			Minimum	Average	Maximum	
	5-24	1-10	20	50	70	2-14
10-20			25	50	80	
>20			>25	>50	>80	
NH ₄ -N	Influent quality (mg/L)	Travel distance (m)	Removal efficiency (%)			Effluent quality (mg/L)
			Minimum	Average	Maximum	
	1.5-2.0	1-2	75	80	85	0.2-0.5
		>	>75	>80	>85	
	Influent quality (mg/L)	Residence/ travel time (days)	Removal efficiency (%)			Effluent quality (mg/L)
			Minimum	Average	Maximum	
1.5-2.0	1-20	75	80	85	0.2-0.5	
		>75	>80	>85		
		Minimum	Average	Maximum		
PO ₄ -P	0.2-16.0	1-30	40	60	80	0.1-3.3
		>30	>40	>60	>80	
	Influent quality (mg/L)	Residence/T ravel time (days)	Removal efficiency (%)			Effluent quality (mg/L)
			Minimum	Average	Maximum	
0.2-16.0	5-40	40	60	80	0.1-3.3	
	>40	>40	>60	>80		
Trace organics	Travel distance (m)		Removal efficiency (%)			
			Minimum	Average	Maximum	
EDTA, NTA, NDC, APEC, CAPEC, NDC, EDC	1-500		80	90	100	
	500-1000		80	90	100	
	>1000		>80	>90	100	
PhACs	500-1000		10	17	20	
	>1000		>10	>17	>20	

Summary: guidelines for estimation of contaminants removal from tertiary effluents during SAT with respect to travel distance and travel time-continue

Contaminant	Residence/Travel time(days)	Removal efficiency (%)		
		Minimum	Average	Maximum
Trace organics EDTA, NTA, NDC, APEC, CAPEC, NDC, EDC	1-300	80	90	100
	300-600	80	90	100
	>600	>80	>90	100
PhACs	300-600	10	17	20
	>600	>10	>17	>20
Microbe	Travel distance (m)	Log removal		
		Minimum	Average	Maximum
Virus	1-2	0.4	1.0	2.5
	2-4	0.5	1.3	2.9
	4-6	1.9	2.9	4
	>6	>1.9	>2.9	>4
Microbe	Residence/Travel time(days)	Log removal		
		Minimum	Average	Maximum
Virus	1-2	0.4	1.1	2.7
	2-4	0.5	2.3	3.0
	>4	1.9	>2.3	>3

It is to be noted that while making a quick assessment of the SAT system using these guidelines, the guideline for microbe removal which is most crucial should be given a priority. However other guidelines should be applied according to needs. It is recommended to choose maximum distances stated in the guidelines in order to reduce risks of pumping water which is not sufficiently treated during SAT.

4.6 General guidelines for DOC removal in the vadose zone and saturated zone during SAT of secondary effluent

Most contaminants are significantly removed during percolation of reclaimed water through the vadose zone. Major purification of the effluent takes place during the vertical flow through the upper layer of recharge basins and the whole vadose zone (Idolevitich and Michail, 1984). However, it is important to allow reclaimed water to flow horizontally in the aquifer (saturated zone) for additional purification, mainly break down of slowly biodegradable organic matter (Drewes *et al.*, 2003; Idolevitich and Michail, 1984). Depending on operation schedule and temperature oxic condition may extend up to 3 m in depth. Figure 4.39 shows that up to about 70% of are removed at travel distance of 1.5 m which is predominantly oxic, reclaimed water is further purified under anoxic conditions. This suggest that in order to get better DOC removal efficiency oxic conditions should be maintained up to about 2.0 m below the surface of recharge basin. Figure 4.40 shows the removal of DOC in the vadoze zone with respect time. Due to the importance of the vadose zone and saturated zone during SAT separate general guidelines were developed (Tables 4.75 and 4.76), Figure 4.40 5, 25, 75, 95 percentile and median

of data used to develop guidelines. The analysis of data was done as shown on Tables 4.73 and 4.74.

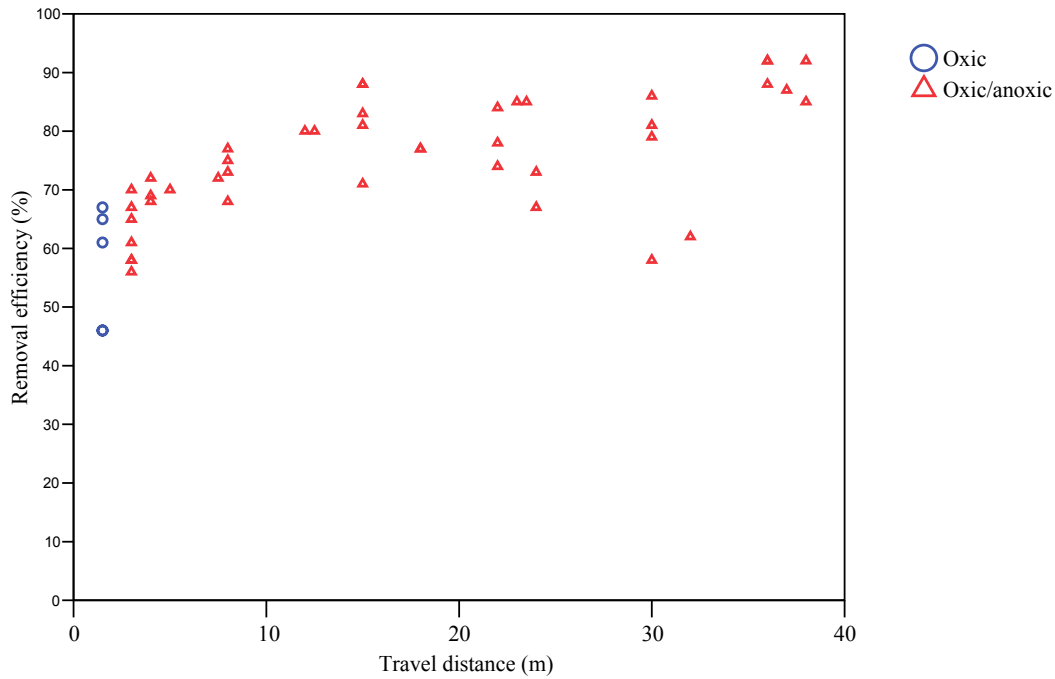


Figure 4.39 DOC removal efficiency vs. travel distance in the vadose zone during soil aquifer treatment of secondary effluents

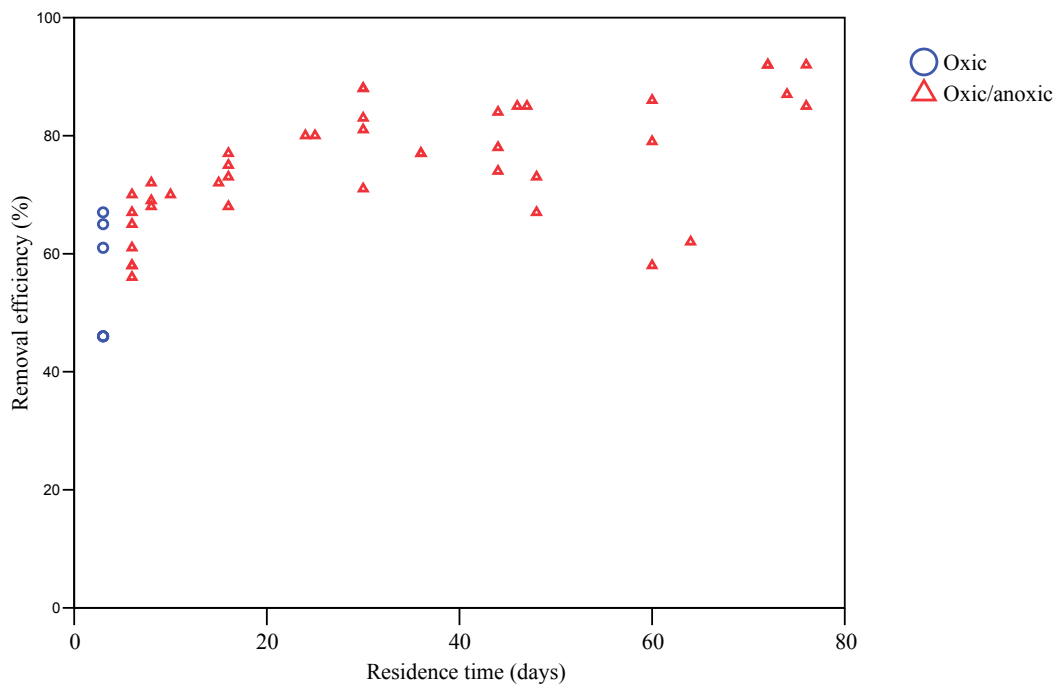


Figure 4.40 DOC removal efficiency vs. travel time in the vadose zone during soil aquifer treatment of secondary effluents

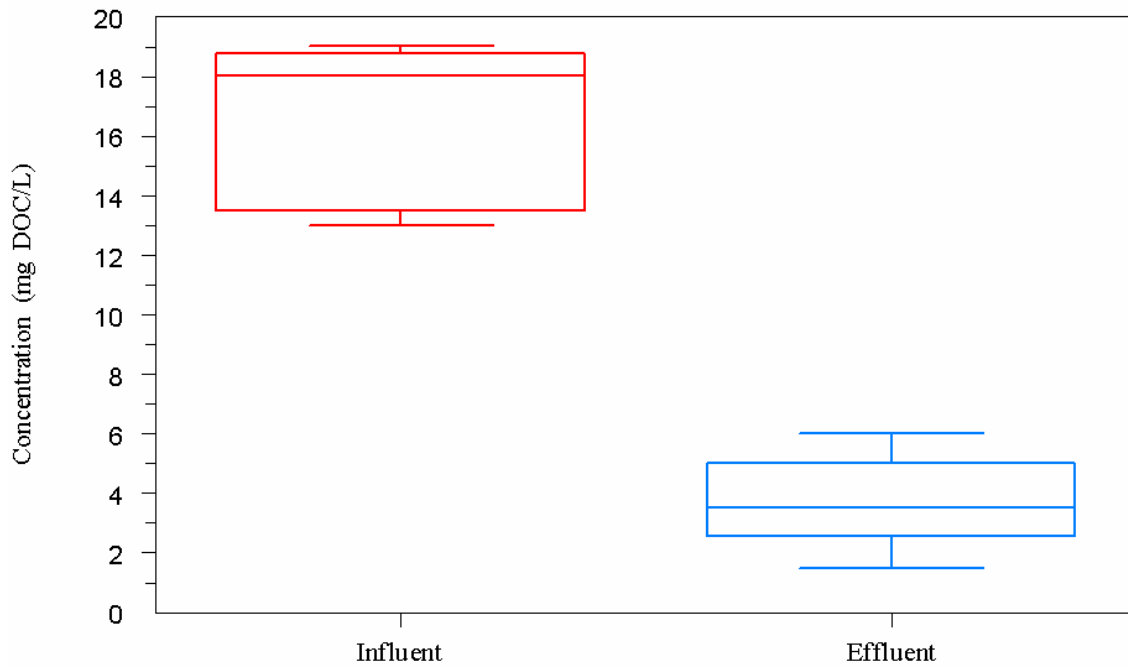


Figure 4.41 Box and Whisker graph for data used in guidelines for DOC removal with respect to travel distance and travel time during soil aquifer treatment of secondary effluents in the vadose zone

Table 4.73 Analysis of DOC removal data for SAT systems treating secondary effluents at different travel distances in the vadose zone and saturated zone

VADOSE ZONE					
Travel Distance (m)	Redox	Removal efficiency (%)		Standard deviation (%)	No. of results
		Range	Average		
1-2	Oxic	46-68	59	10	6
2-10	Oxic/anoxic	56-70	63	6	8
10-20	Oxic/anoxic	72-73	73	1	2
20-40	Oxic/anoxic	77-88	77	12	9
SATURATED ZONE					
Travel Distance (m)	Redox	Removal efficiency (%)		Standard deviation (%)	No. of results
		Range	Average		
>40	Oxic/anoxic	77-94	83	8	7

Table 4.74 Analysis of DOC removal data for SAT systems treating secondary effluents at different residence/travel times

VADOSE ZONE					
Travel time (days)	Redox	Removal efficiency (%)		Standard deviation (%)	No. of results
		Range	Average		
1-3	Oxic	46-68	59	10	6
3-10	Oxic/anoxic	56-70	63	6	8
10-20	Oxic/anoxic	72-73	73	1	2
20-80	Oxic/anoxic	77-88	77	12	9
SATURATED ZONE					
Travel time (days)	Redox	Removal efficiency (%)		Standard deviation (%)	No. of results
		Range	Average		
>180	Oxic/anoxic	77-94	83	8	7

Based on the data analysis shown on Tables 4.73 and 4.74 above, and assuming that DOC is contributed by infiltrates from the recharge source only, and redox and biomass conditions are sufficient to influence DOC removal. Also assuming that in general under the normal operating conditions DOC removal increases with travel distance and residence/travel time, the guideline were developed as shown in Tables 4.75 and 4.76.

Table 4.75 Guidelines for DOC removal data for SAT systems treating secondary effluents at different travel distances in the vadose zone and saturated zone

VADOSE ZONE						
Influent quality (mg/L)	Travel Distance (m)	Redox	Removal efficiency (%)			Effluent quality (mg/L)
			Minimum	Average	Maximum	
13-19	1-2	Oxic	40	60	70	1-7
	2-20	Oxic/anoxic	60	65	75	
	20-40	Oxic/anoxic	70	75	90	
SATURATED ZONE						
Influent quality (mg/L)	Travel Distance (m)	Redox	Removal efficiency (%)			Effluent quality (mg/L)
			Minimum	Average	Maximum	
13-18	>40	Oxic/anoxic	75	80	95	1-5

Table 4.76 Guidelines for DOC removal data for SAT systems treating secondary effluents at different residence/travel times

VADOSE ZONE						
Influent quality (mg/L)	Travel time (days)	Redox	Removal efficiency (%)			Effluent quality (mg/L)
			Minimum	Average	Maximum	
13-19	1-3	Oxic	40	60	70	1-7
	3-20	Oxic/anoxic	60	65	75	
	>20	Oxic/anoxic	70	75	90	
SATURATED ZONE						
Influent quality (mg/L)	Travel time (days)	Redox	Removal efficiency (%)			Effluent quality (mg/L)
			Range	Average	Maximum	
13-18		Oxic/anoxic	77-94	83	8	1-5

4.7 Influence of soil type and travel time on DOC removal from secondary effluent during SAT

Soil aquifer treatment of secondary effluent was studied to determine the influence of soil type on DOC removal since more SAT systems treat secondary effluents. However, DOC has an influence on removal of nitrogen. The results presented in Table 4.77 shows that travel time has more influence on DOC removal than travel distance. Generally soil type may have a significant influence on DOC removal since, at comparable travel time, sandy loam SAT column provided higher DOC removal efficiency than poorly graded sand and silica sand SAT columns. Longer travel times allow breakdown of slowly biodegradable organics (Idolevitich and Michail, 1984). Katukiza (2006) also found that decreasing travel time reduces DOC removal during SAT. Sandy loam is likely to be better for SAT as a consequence of more surface area for biomass attachment since it contains about 50% fine soil. However, to confirm this, lab-scale SAT has to be set up and operated under same parameters/processes and influent characteristics. The parameters/processes to be considered include redox condition, hydraulic loading rate (HLR), temperature, composition of organic fractions, and biomass concentration.

Table 4.77 Influence of soil type on DOC removal during SAT

Soil type	Influent quality (mg/L)	Travel distance (m)	Travel time (days)	SAT	Removal efficiency (%)
Sandy loam	14	0.82	7	2 soil column	59-73
	11	1	1	1 soil columns	54
	15	2.5	3	1 soil column	53
Poorly graded sand	4-12	1	1-2	3 soil columns	26-48
Silty sand	12	1	3	1 soil column	44
Silica sand	4-8	0.3	1	2 soil columns	33-46
	8	1.0	1	1 soil column	29
	11-14	5	2-4	1 soil column	15-30
Poorly graded silty sand	13	1.0-2.0	2-4	Site	56

4.8 Influence of redox conditions on DOC removal from secondary effluent during SAT

Redox condition condition influences removal of contaminants by biochemical processes. The removal of DOC, Ammonia and nitrate are strongly influence by redox conditions. Some bacteria die when redox condition changes, the bacteria that depend on oxidic condition to survive would die under anoxic condition and vice versa. During field SAT the removal of contaminants is through oxidic condition followed by anoxic condition. Figures 4.42 and 4.43 show the performance of SAT systems in removal of DOC under different redox conditions. During SAT dissolved oxygen decreases as wastewater percolates through the vadose zone and redox potential decreases, anoxic condition develops and Nitrate become the next electron acceptor (Fox *et al.*, 2001b). Depending on operation schedule and temperature oxidic condition may extend up to 3 m in depth. Yoo *et al.*,(2006) found that during drying SAT system reached near atmospheric level of oxygen (18%) to a depth of approximately 1.0 m. Below 1.0 m the oxygen content decreased sharply but some oxygen (3%) was present at 3.0 m below surface of recharge basin.

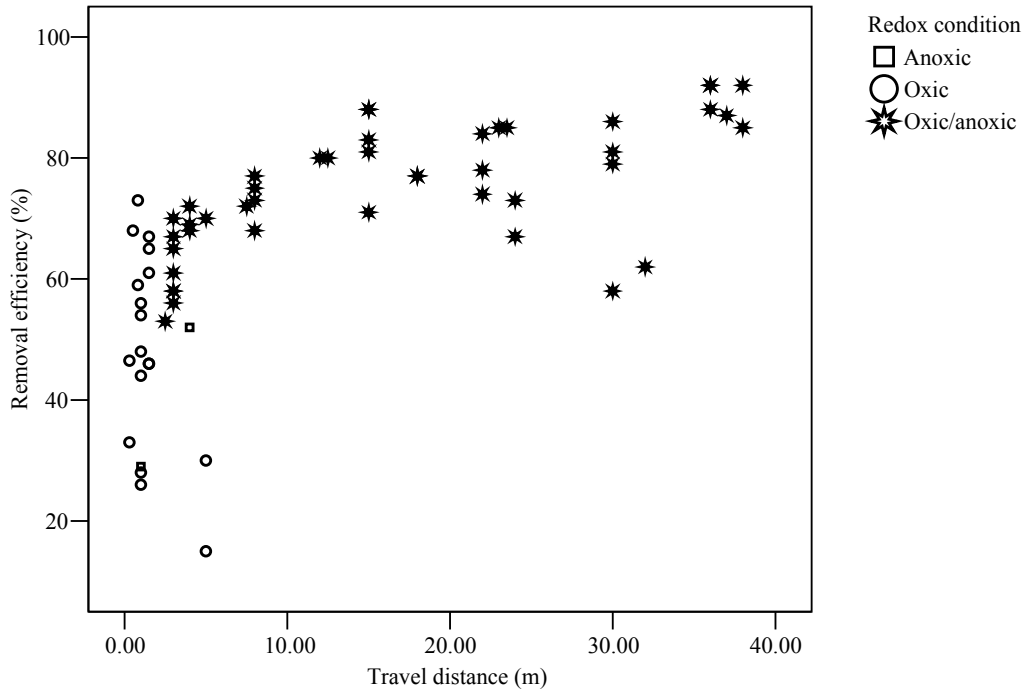


Figure 4.42 Removal of DOC from secondary effluents under different redox conditions with respect travel distance

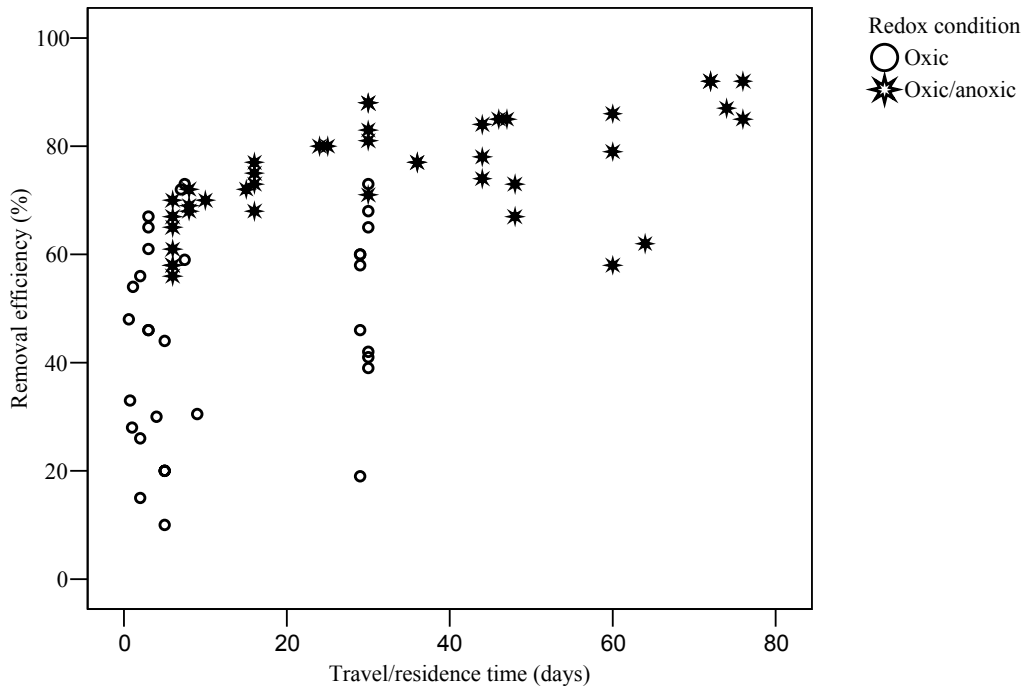


Figure 4.43 Removal of DOC from secondary effluents under different redox conditions with respect travel distance and travel time

Table 4.78 shows the performance of SAT systems under different redox conditions which shows that DOC can virtually be reduced significantly under oxidic and anoxic conditions separately. However, during SAT at field sites both oxidic and anoxic conditions take part in removal of DOC starting with oxidic conditions followed by anoxic conditions.

Table 4.78 Influence of redox conditions on DOC removal during SAT

Redox condition	Influent quality (mg/L)	Travel distance (m)	Travel time (days)	SAT	Removal efficiency (%)
Oxic	4-15	0.3-5.0	1-4	13 soil columns	15-73
	13-15	0.5-1.5	3	2 Field site	46-68
Anoxic	8.6	1	-	1 soil columns	29
		4	-	1 soil columns	52
Oxic/Anoxic	13-19	1.5-38	3-76	3 field sites	46-85

4.9 Testing the developed guideline to predict water quality during SAT

The guidelines (Tables 4.29 and 4.30) were tested using the results of simulated SAT in soil columns which were operated under continuous aerobic condition at UNESCO-IHE laboratory on October 2006 to March 2007 in column studies by Musabe (2007). The results show that this SAT has a performance which is below average since the estimated

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average effluent as shown in Table 4.79 is less than the measured effluent quality. It is most likely that effluent fed to this SAT characterised with more NBDOC than BDOC. The effluent quality was estimated by using removal efficiencies shown in guidelines for removal of DOC from secondary effluents. Furthermore, Primary, secondary and tertiary effluents with DOC concentration within the range of developed guideline were extracted from literature, and used to demonstrate how the guidelines can be applied in practice (Tables 4.80-4.82).

Table 4.79 Guidelines testing for estimation of DOC removal from secondary effluents during SAT

Influent quality (mg/L)	Travel Distance (m)	Estimated effluent quality (mg/L)			Measured Effluent quality (mg/L)
		Maximum	Average	Minimum	
16.1	5	13.7	8.0	4.8	11.6
Influent quality (mg/L)	Travel time (days)	Estimated effluent quality (mg/L)			Measured Effluent quality (mg/L)
		Maximum	Average	Minimum	
16.1	4	14.5	8.0	4.8	11.6

Table 4.80 Application of guidelines to estimate removal of DOC from primary effluent (Influent data source: Rice and Bouwer., 1984)

Influent quality (mg/L)	Travel Distance (m)	Expected effluent quality (mg/L)		
		Maximum	Average	Minimum
24	≤1	22	14	10
	>1	<22	<14	<10
Influent quality (mg/L)	Travel time (days)	Estimated effluent quality (mg/L)		
		Maximum	Average	Minimum
24	1-10	22	14	10
	10-30	19	13	10
	>30	<19	<13	<10

Table 4.81 Application of guidelines to estimate removal of DOC from secondary effluent (Influent data source: Quanrud et al., 2002)

Influent quality (mg/L)	Travel Distance (m)	Expected effluent quality (mg/L)		
		Maximum	Average	Minimum
13	1-5	11	7	4
	5-25	4	3	1
	>25	<4	<3	<1
Influent quality (mg/L)	Travel time (days)	Estimated effluent quality (mg/L)		
		Maximum	Average	Minimum
13	1-10	12	7	4
	10-30	10	5	1
	30-50	4	3	1
	>50	<4	<3	<1

Table 4.82 Application of guidelines to estimate removal of DOC from tertiary effluent (Influent data source: Drewes et al., 2003)

Influent quality (mg/L)	Travel Distance (m)	Expected effluent quality (mg/L)		
		Maximum	Average	Minimum
5.64	1-5	5	3	2
	5-15	3	2	1
	>15	<3	<2	<1
Influent quality (mg/L)	Travel time (days)	Estimated effluent quality (mg/L)		
		Maximum	Average	Minimum
5.64	1-10	5	3	2
	10-20	4	3	1
	>20	<4	<3	<1

4.10 Application scope and limitations of the guidelines developed

It should be noted that these guidelines are developed from few available literature (52) found within a limited time of research. Most data used in developing guidelines come from column studies using different soils and few from field studies operated under different conditions using influent (mostly pre-treated domestic wastewater) of different characteristics. Therefore, these guidelines should be used for preliminary estimation of effluent quality of soil aquifer treatment systems. However, they could give some idea on what can be expected from an SAT system under general operating conditions that will result in some time saving in design of detailed field-site and laboratory pilot works.

4.11 Framework for application and transfer of SAT technology

A successful transfer of technology can occur if the recipient is sufficiently capable of maintaining and fully utilizing the technology. Technology transfer requires critical evaluation of the social and economic impact of the proposed technology to the recipient country (Madu, 1989). Technology transfer is often faced with socioeconomic and political problems that must be identified. These factors are structurally dependent and as such for each individual host country (Madu, 1989; Saad *et al.*, 2002). Local service organisations are the proper recipient of technology transfer since the likelihood of achieving compatible goals will be higher (Al-Ali, 1991; Ekholm, 1988; Niosi *et al.*, 1995). The success of transfer of technology will be reflected on needs and expected benefits. There are two types of transfer of technology namely; vertical transfer and horizontal transfer (Bennett, 2002). The vertical transfer involves a) research b) development and c) Implementation/production. Horizontal transfer involves transfer of technology from one operational environment to another. Most developing countries are involved in horizontal transfer of technology. Processes to be followed for successful transfer of SAT technology are proposed as shown in Figure 4.36.

The process starts with identification of potential stakeholders who are relevant to the transfer of technology. These stakeholders are those who will be influenced or will influence the decisions arrived at. The next step is to define realistic needs and objectives which can be achievable by appropriate wastewater treatment technology. Before SAT technology is adopted, the scope and limitations of existing technology have to be

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studied. Strength and weaknesses of resources which include human and natural resources should be identified by stakeholders. Weaknesses may suggest a need to develop more capabilities before SAT technology can be transferred. However, studies may show that the existing technology meets the needs and objectives therefore, it may not be necessary to transfer SAT technology. If studies show that SAT technology will meet need and objective then the technology should be adopted after approval by relevant institutions of the recipient country.

The imported technology has to be accepted, monitored, maintained and used implying successful transfer of technology. Adoption of technology should not end the process of transfer. There is need to establish a control system to continuously or periodically evaluate the success or failure of new technology. Some failure may be traceable to the production process and may be corrected. Since many wastewater infrastructures are managed by government agencies it is advised that the SAT technology be transferred and managed by these agencies. Their experience in managing wastewater infrastructure may be useful for the success of SAT technology imported.

The framework for application of SAT consists of six steps as elaborated below;

i) Characterisation and Quantification of effluents

The information required:

- Type of pre-treatment processes available
- Origin of effluents
- Effluent flow rates

ii) Comparison of SAT to alternative technologies

The information required:

- Removal efficiencies
- Investment costs
- Operation and maintenance costs
- Storage requirements
- Robustness
- Simplicity of operation

Select SAT technology if it is appropriate for the given area.

iii) Site investigations to determine the feasibility of SAT technology

The information required:

- Proximity to neighbourhoods, wastewater treatment plants and irrigation schemes.
- Soil profile
- Groundwater hydrology
- pH

iv) Estimation of water quality based on developed guidelines

The information required:

- Travel distance (m)
- Travel/residence time (days)
- Influent quality
- Water quality guidelines and regulations

v) Determination of land required for SAT system

The information required:

- Quantity and characteristic of effluent
- Soil profile
- Hydraulic conductivity of soil
- Groundwater hydrology
- Distance to groundwater
- Seasonal variation in temperature

vi) Estimation of capital and operation and maintenance costs

The information required:

- Material cost for construction of basins, wells, installation of suction lysimeters.
- Labour cost for construction and operation and maintenance
- Energy and chemicals
- Fees if any

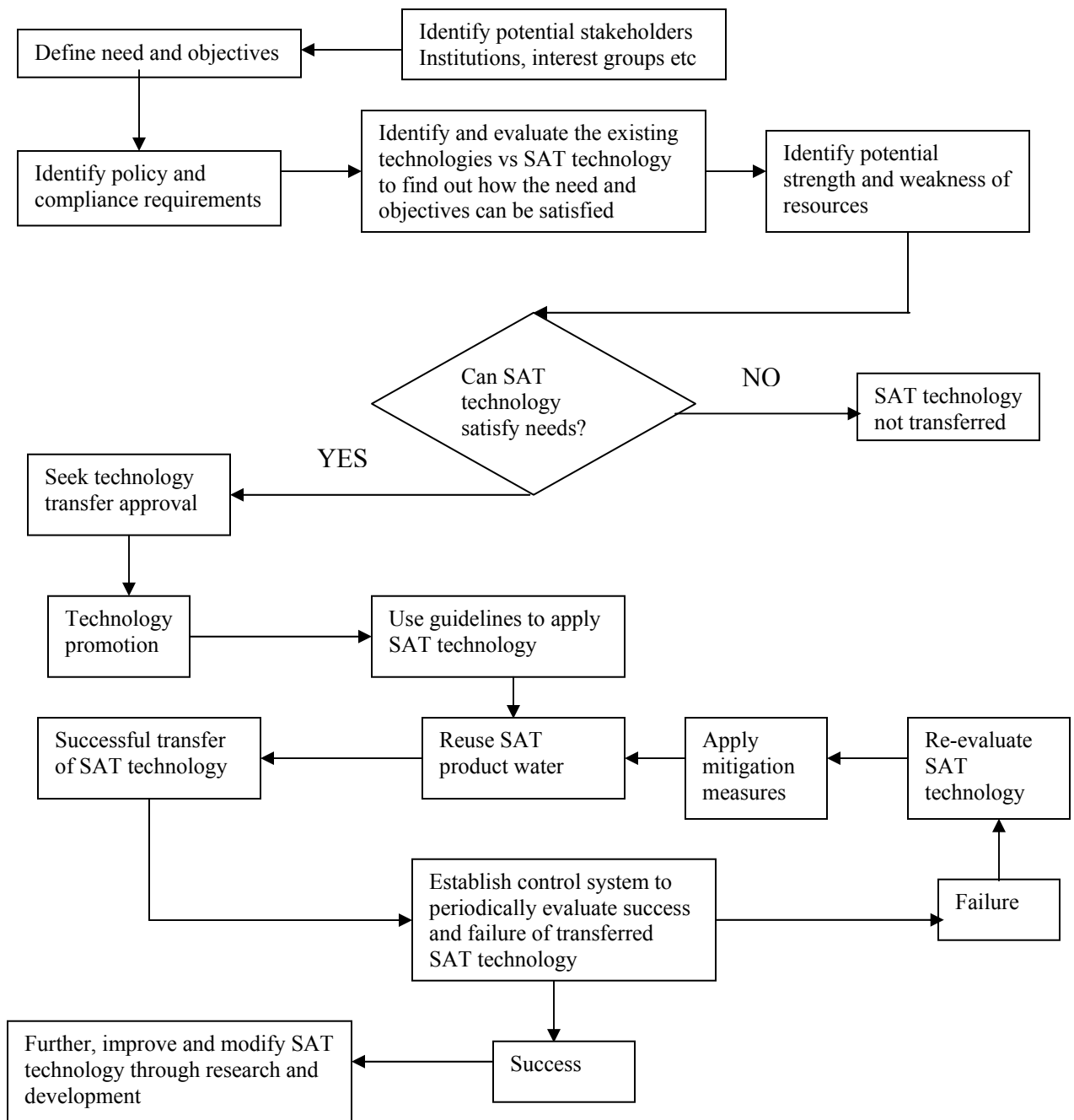


Figure 4.44 Framework for transfer of SAT technology

5.0 CONCLUSIONS AND RECOMMENDATIONS

Based on extensive literature review, data analysis and discussion of results the following conclusions and recommendations were made.

5.1 Conclusions

- 1) The removal of contaminants during SAT are case specific and may not be presented using one kinetic model.
- 2) A higher removal of about 50% and 80% for DOC and ammonia respectively during field SAT of secondary and tertiary effluents takes place in the top 1.5 m of soil which is mostly under predominant oxic condition.
- 3) Biodegradation is the main mechanism for removal of DOC which makes its removal sustainable.
- 4) Generally the removal of contaminants increases with residence/travel time and travel distance. Travel time has more influence on DOC removal than travel distance,
- 5) Typical influent DOC for primary, secondary and tertiary SAT was 24-35 mg/L, 10-15 mg/L, 5-12 mg/L respectively. Typical effluent DOC for primary, secondary and tertiary SAT was 14-18 mg/L, 2-8 mg/L, 2-10mg/L. respectively.
- 6) DOC removal efficiencies during SAT of secondary and tertiary effluents at a travel distance of 5.0 m are comparable as 15-73% and 19-72% for secondary and tertiary effluents respectively. DOC concentration of SAT product water was <2 mg/L for long term SAT of both secondary and tertiary effluent which is below the average DOC found in drinking water supply which is 2.2 mg/L in field sites, therefore tertiary treatment prior to SAT may not be needed.
- 7) Primidone and carbomezapine was persistent during SAT of secondary effluent but was removed during SAT of tertiary effluent which suggest that contaminants persistent to one SAT system is not likely to be persistent to another.
- 8) Phosphorus removal during SAT is not sustainable since its removal mechanism is mainly adsorption and there breakthrough is most likely when the soil adsorption capacity is exceeded.
- 9) There is no need to reduce nutrient load from wastewater where water is used for unrestricted irrigation. Where direct potable reuse is needed, nutrient should be significantly reduced. Therefore design of SAT system depends on intended reuse of SAT effluent.
- 10) Sandy loam soil is most likely to be the best soil for SAT systems since it has demonstrated better DOC removal efficiency as compared to other soil types.
- 11) Generally average bacteria removal was >4 log at travel distance <10 m and virus removal was >2 log at travel distance <10 m.
- 12) Some SAT systems removed microbes below detection, this implies that disinfection of effluent prior to SAT is not needed

5.2 Recommendations

- 1) More studies should be done on removal of multiple contaminants during SAT of primary effluents. The findings could encourage developing countries to apply SAT technology as it is cheaper to treat wastewater to primary level prior to SAT.
- 2) Heterotrophic denitrification was hardly achieved during SAT, therefore possibilities of enhancement of heterotrophic denitrification during SAT should be investigated.
- 3) A similar study to include the effect of wastewater temperature, oxygen concentration, DOC fractions, biomass concentration, soil salinity and pH on contaminants removal should be investigated and included in the guidelines.
- 4) Human health risks associated with use of SAT product water should be thoroughly investigated when direct potable reuse is considered.
- 5) This study revealed that more studies have been done on DOC removal as compared to removal of other contaminants during SAT. Equally important the removal of other contaminants particularly microbes during SAT under different operating conditions and soils should be investigated since microbial quality is main concern to public health.
- 6) Environmental impact assessment (EIA) should be done before implementing SAT system at field-scale.

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APPENDIX A: Removal of DOC from primary effluent by batch and field SAT systems under different operating conditions

SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature condition (°C)	Influent DOC (mg/L)	effluent DOC (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
1	Katukiza, 2006	Batch reactors	Silica sand	-	-	Aerobic	7	34.66	14.56	N/A	N/A	15.00	58.00
		Batch reactors	Silica sand	-	-	Anoxic	7	35.00	17.85	N/A	N/A	15.00	49.00
2	Cha et al., 2004a	Batch reactors	Poorly graded sand	-	-	Aerobic	-	9.90	7.02	N/A	N/A	29.00	29.00
3	Rice and Bouwer, 1984	Field study	Loamy sand	7	7-21	Oxic	-	24.00	16.00	0.10-1.70	0.10	0.11	33.00
						Oxic	-	24.00	15.00	0.10-1.70	0.56	0.62	37.00
			Sandy loam	7	7-21	Oxic	-	24.00	21.00	0.10-1.70	0.10	0.11	12.00
						Oxic	-	24.00	18.00	0.10-1.70	0.56	0.62	25.00
						Oxic	-	24.00	10.00	0.10-1.70	0.10	0.11	58.00
						Oxic	-	24.00	9.00	0.10-1.70	0.46	0.51	62.00
						Oxic	-	24.00	19.00	0.10-1.70	0.10	0.11	21.00
Oxic	-	24.00	11.00	0.10-1.70	0.53	0.59	54.00						

APPENDIX B: Removal of NH4-N from primary effluent by field SAT systems under different operating conditions

SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature condition (°C)	Influent NH ₄ -N (mg/L)	effluent NH ₄ -N (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
1	Nema et al., 2001	Field study	alluvium	7	7-21	Oxic/anoxic	-	42	21	0.04-0.12			50.00
2	Rice and Bouwer, 1984	Field study	Loamy sand	7	7-21	Oxic	-	24.00	15.00	0.10-1.70	0.10	0.11	37.00
						Oxic	-	24.00	8.40	0.10-1.70	0.56	0.62	65.00
			Sandy loam	7	7-21	Oxic	-	24.00	18.10	0.10-1.70	0.10	0.11	25.00
						Oxic	-	24.00	9.60	0.10-1.70	0.56	0.62	60.00
						Oxic	-	24.00	2.00	0.10-1.70	0.10	0.11	92.00
						Oxic	-	24.00	1.20	0.10-1.70	0.46	0.51	95.00
						Oxic	-	24.00	1.00	0.10-1.70	0.10	0.11	96.00
Oxic	-	24.00	0.40	0.10-1.70	0.53	0.59	98.00						

APPENDIX C: Removal of PO₄-P from primary effluent by field and soil column SAT systems under different operating conditions

SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature (°C)	Influent PO ₄ -P (mg/L)	effluent PO ₄ -P (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
1	Nema et al., 2001	Field study	alluvium	7	7	Oxic/anoxic		3.50	0.35	0.04-0.12 (0.08)	25.00		90.00
2	Lance et al., 1980	Soil column	Loamy sand	9	5	Oxic/anoxic	22-25	7.20	2.23	0.18	2.75	15.71	66.00-72.00 (69.00)
3	Rice and Bouwer, 1984	Field study	Loamy sand	7	7-21	Oxic	-	5.50	6.70	0.10-1.70 (0.90)	0.10	0.11	-22.00
						Oxic	-	5.50	5.30	0.10-1.70 (0.90)	0.56	0.62	4.00
			Sandy loam	7	7-21	Oxic	-	5.50	6.50	0.10-1.70 (0.90)	0.10	0.11	-18.00
						Oxic	-	5.50	0.90	0.10-1.70 (0.90)	0.56	0.62	84.00
						Oxic	-	5.50	4.70	0.10-1.70 (0.90)	0.10	0.11	15.00
						Oxic	-	5.50	4.30	0.10-1.70 (0.90)	0.46	0.51	22.00
						Oxic	-	5.50	3.60	0.10-1.70 (0.90)	0.10	0.11	35.00
						Oxic	-	5.50	2.80	0.10-1.70 (0.90)	0.53	0.59	49.00

APPENDIX D : Removal of trace organics from primary effluent by field SAT systems under different operating conditions

SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater Temperature condition (°C)	Trace organic type and concentration unit	Influent concentration	effluent concentration	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
1	Hutchins et al., 1983	Field study	Poorly graded sand	6	16	Oxic/anoxic	-	Toluene (µg/L)	89.00	0.00	-	-	-	100
				6	16	Oxic/anoxic	-	o-Xylene (µg/L)	1.20	0.30	-	-	-	75
				6	16	Oxic/anoxic	-	o-Ethyltoluene (µg/L)	6.50	0.30	-	-	-	95
				6	16	Oxic/anoxic	-	sec-Butylbenzene (µg/L)	11.00	0.00	-	-	-	100
				6	16	Oxic/anoxic	-	p-Dichlorobenzene (µg/L)	3.20	0.65	-	-	-	80
				6	16	Oxic/anoxic	-	Linalool (µg/L)	2.40	0.00	-	-	-	100
				6	16	Oxic/anoxic	-	m-Cresol (µg/L)	66.00	0.00	-	-	-	100
				6	16	Oxic/anoxic	-	2,5-Dimethyl-2,5 hexanediol (µg/L)	28.00	0.04	-	-	-	99.98
				6	16	Oxic/anoxic	-	x-Terpeneol (µg/L)	85.00	0.00	-	-	-	100
				6	16	Oxic/anoxic	-	p-Allylanisole (µg/L)	4.10	0.00	-	-	-	100
				6	16	Oxic/anoxic	-	Naphthalene (µg/L)	4.90	0.20	-	-	-	96
				6	16	Oxic/anoxic	-	2-Methylnaphthalene (µg/L)	3.90	0.00	-	-	-	100
				6	16	Oxic/anoxic	-	Indole (µg/L)	11.00	0.00	-	-	-	100
				6	16	Oxic/anoxic	-	3,4-Dichloroaniline (µg/L)	6.10	0.00	-	-	-	100
				6	16	Oxic/anoxic	-	Dimethyl phthalate (µg/L)	9.40	1.40	-	-	-	85
				6	16	Oxic/anoxic	-	o-Phenylphenol (µg/L)	49.00	2.70	-	-	-	94

APPENDIX E : Removal of microbes from primary effluent by field and soil column SAT systems under different operating conditions

SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature condition (°C)	Microbe name and concentration unit	Influent	effluent	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Log removal
1	Nema et al., 2001	Field study	alluvium	7	7	Oxic/anoxic	-	Total coliform (MPN/100ml)	2 x 10 ⁷	630	0.04-0.12	25.00	250.00	4.50
								Faecal coliform (MPN/100ml)	3x10 ⁶	95	0.04-0.12	25.00	250.00	4.50
								Faecal streptococci (MPN/100ml)	2.8 x 10 ⁶	89	0.04-0.12	25.00	250.00	4.50
2	Lance <i>et al.</i> , 1980	Soil column	Loamy sand	9	5	Oxic/anoxic	22-25	Total coliform (MPN/100ml)	0.65-20 (10.325) x 10 ⁶	0.-186 (93)	0.18	2.75	15.71	5.00
		Soil column						Polio virus (plaque-forming unit-pfu)	1.2 x 10 ⁴	0	0.18	0.80	4.57	4.00
3	Rice and Bouwer, 1984	Soil column	-	-	-	Oxic	-	Faecal coliform (MPN/100ml)	8x10 ⁶	0-50		0.46-0.56		6.90

APPENDIX F: Removal of DOC from secondary effluent batch, soil column and field SAT systems under different operating conditions

SN	Literature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature condition (°C)	Influent DOC (mg/L)	effluent DOC (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
1	Westerhoff and Pinney, 2000	Soil columns	sandy loam	7	7	Oxic	4	13.80	3.74	0.11	0.82	7	73
	Westerhoff and Pinney, 2000	Soil columns	sandy loam	7	7	Oxic	4	14.10	5.80	0.11	0.82	7	59
	Westerhoff and Pinney, 2000	Batch reactors	sandy loam	-	-	Oxic	-	20.40	5.63	N/A	N/A	7	72
2	Quanrud <i>et al.</i> , 1996b	Soil columns	Poorly graded sand	7	7	Oxic (Aerated)	25	12.35	6.42	0.30-3.00	1.00	1	48
			sandy loam	7	7	Oxic (Aerated)	25	12.35	5.53	0.60-1.20	1.00	2	56
			Silty sand	7	7	Oxic (Aerated)	25	12.35	8.15	0.50-0.10	1.00	5	44
3	Quanrud <i>et al.</i> , 1996a	Soil columns	Sandy loam	7	7	Oxic	24-26	11.00	5.00	0.90	1.00	1	54
4	Quanrud <i>et al.</i> , 2003a	Batch reactors	Poorly graded silty sand	-	-	Oxic	-	3.00	2.70	N/A	N/A	5	10
			Poorly graded silty sand	-	-	Oxic	-	6.00	4.80	N/A	N/A	5	20
			Poorly graded silty sand	-	-	Oxic	-	20.00	16.00	N/A	N/A	5	20
5	Quanrud <i>et al.</i> , 2003c	Field study	Clay lenses	7	7	Oxic	-	15.00	5.00	0.50	1.50	3	67
						Oxic/anoxic		15.00	5.20	0.50	3.00	6	65
						Oxic/anoxic		15.00	4.50	0.50	5.00	10	70
						Oxic/anoxic		15.00	3.00	0.50	12.50	25	80
						Oxic/anoxic		15.00	3.50	0.50	18.00	36	77
						Oxic/anoxic		15.00	4.00	0.50	24.00	48	73
						Oxic/anoxic		15.00	2.00	0.50	37.00	74	87
						Oxic		13.00	7.00	0.50	1.50	3	46
						Oxic/anoxic		13.00	5.50	0.50	3.00	6	58
						Oxic/anoxic		13.00	3.70	0.50	7.50	15	72
						Oxic/anoxic		13.00	1.50	0.50	15.00	30	88
		Oxic/anoxic		13.00	2.00	0.50	23.50	47	85				
		Oxic/anoxic		13.00	5.50	0.50	30.00	60	58				
6	Katukiza, 2006	Soil columns	silica sand	4	No	Oxic	-	14.77	10.34	< 1.25	5	4	30
			silica sand	2	No	Oxic	-	11.57	9.79	< 2.50	5	2	15
7	Cha <i>et al.</i> , 2004a	Soil column	Poorly graded sand	4	3	Oxic	4	4.30	3.20	0.53	1.00	2	26
		Batch reactors	Poorly graded sand	-	-	Oxic	4	5.00	2.00	N/A	N/A	29	60
			Poorly graded sand	-	-	Oxic	4	8.60	3.60	N/A	N/A	29	58
			Poorly graded sand	-	-	Oxic	4	1.60	1.30	N/A	N/A	29	19
			Poorly graded sand	-	-	Oxic	4	3.70	2.00	N/A	N/A	29	46

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SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature condition (°C)	Influent DOC (mg/L)	effluent DOC (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
7	Cha et al., 2004a	Batch reactors	Poorly graded sand	-	-	Oxic	4	9.90	6.93	N/A	N/A	29	30
			Poorly graded sand	-	-	Oxic	4	2.30	1.73	N/A	N/A	29	25
			Poorly graded sand	-	-	Oxic	4	2.60	1.40	N/A	N/A	29	60
8	Cha et al., 2005	Soil column	Poorly graded sand	4	3	Oxic	20	4.50	3.38	1.34	1.00	1	28
9	Idolevitch et al., 2003	Field study	Sandy soils	-	-	Oxic/anoxic	-	17.50	4.50	1.75	300.00	Months	74
10	A.Kanarek and Michail, 1996	Field study	Sandy soils	1	2-3	Oxic/anoxic	-	17.00	3.90	-	350-1500	Months	77
		Field study	Sandy soils	2	2-4	Oxic/anoxic	-	14.00	2.40	-	350-1500	Months	83
11	Amy and Drewes, 2006a	Field study	-	-	-	Oxic/anoxic	-	14.10	0.98	-	418	Months	93
12	Idolevitch and Michail, 1984	Field study	Sand stone	1	2-3	Oxic/anoxic	-	18	3.2	1.50-2.00	1020	6-12 months	82
13	Kanarek <i>et al.</i> , 1993	Field study	Sandy soil	1	2-3	Oxic/anoxic	-	13.00	3.3	-	350-1500	Months	75
14	Rauch and Drewes, 2005	Soil columnn	Silica sand	-	-	Oxic	-	7.00-9.50	4.41	-	0.30	-	47
		Batch reactors	Silica sand	-	-	Oxic	-	7.00-9.50	5.73	-	N/A	9	31
15	Cha <i>et al.</i> , 2004b	Batch reactors	Sandy soil	-	-	Oxic	23-25	10.00	2.70	-	N/A	30	73
			Sandy soil	-	-	Oxic	23-25	15.00	4.80	-	N/A	30	68
			Sandy soil	-	-	Oxic	23-25	20.00	7.00	-	N/A	30	65
			Sandy soil	-	-	Oxic	23-25	12.00	7.10	-	N/A	30	41
			Sandy soil	-	-	Oxic	23-25	18.00	10.50	-	N/A	30	42
			Sandy soil	-	-	Oxic	23-25	24.00	14.70	-	N/A	30	39
16	Yoo <i>et al.</i> , 2006	Field study	Poorly graded silty sand (1-2 m)	3	4	Oxic/anoxic	-	13.54	5.89	0.50	3	6	56
		Field study	Poorly graded silty sand (1-2 m)	3	4	Oxic/anoxic	-	13.54	1.10	0.50	38	76	92
		Field study	Poorly graded silty sand (1-2 m)	3	4	Oxic/anoxic	-	13.21	5.21	0.50	3	6	61
		Field study	Poorly graded silty sand (1-2 m)	3	4	Oxic/anoxic	-	13.21	2.00	0.50	38	76	85
17	Jarusutthirak <i>et al.</i> , 2003	Field study	-	-	-	Oxic/anoxic	-	13.59	0.83	-	70	60	94
18	Rauch and Drewes, 2004	Soil column	Silica sand	-	-	Oxic	-	4.46	3.00	0.40	0.30	1	33

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SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature condition (°C)	Influent DOC (mg/L)	effluent DOC (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)		
19	Fox et al., 2001b	Field study	-	3	4	Oxic	-	13.00	7.00	0.50	1.50	3	46		
				3	4	Oxic/anoxic	-	13.00	5.50	0.50	3.00	6	58		
				3	4	Oxic/anoxic		13.00	3.50	0.50	8	16	73		
				3	4	Oxic/anoxic		13.00	1.50	0.50	15	30	88		
				3	4	Oxic/anoxic		13.00	2.00	0.50	23	46	85		
				3	4	Oxic/anoxic		13.00	5.00	0.50	30	60	62		
				3	4	Oxic		15.00	5.20	0.50	1.50	3	65		
				3	4	Oxic/anoxic	-	15.00	5.00	0.50	3.00	6	67		
				3	4	Oxic/anoxic		15.00	3.00	0.50	12.00	24	80		
				3	4	Oxic/anoxic		15.00	3.50	0.50	18.00	36	77		
				3	4	Oxic/anoxic		15.00	5.00	0.50	24.00	48	67		
				3	4	Oxic		15.00	5.80	0.50	1.50	3	61		
				-											
				-	3	4	Oxic/anoxic		19.00	6.00	0.50	4.00	8	68	
				-	3	4	Oxic/anoxic		19.00	6.00	0.50	8.00	16	68	
				-	3	4	Oxic/anoxic		19.00	5.50	0.50	15.00	30	71	
				-	3	4	Oxic/anoxic		19.00	5.00	0.50	22.00	44	74	
				-	3	4	Oxic/anoxic		19.00	4.00	0.50	30.00	60	79	
				-	3	4	Oxic/anoxic		19.00	1.50	0.50	36.00	72	92	
				-	3	4	Oxic/anoxic		18.00	5.00	0.50	4.00	8	72	
				-	3	4	Oxic/anoxic		18.00	4.50	0.50	8.00	16	75	
				-	3	4	Oxic/anoxic		18.00	3.00	0.50	15.00	30	83	
				-	3	4	Oxic/anoxic		18.00	2.80	0.50	22.00	44	84	
				-	3	4	Oxic/anoxic		18.00	2.50	0.50	30.00	60	86	
				-	3	4	Oxic/anoxic		18.00	1.50	0.50	36.00	72	92	
				-	3	4	Oxic/anoxic		13.00	4.00	0.50	4.00	8	69	
				-	3	4	Oxic/anoxic		13.00	3.00	0.50	8.00	16	77	
				-	3	4	Oxic/anoxic		13.00	2.50	0.50	15.00	30	81	
	-	3	4	Oxic/anoxic		13.00	2.80	0.50	22.00	44	78				
	-	3	4	Oxic/anoxic		13.00	2.50	0.50	30.00	60	81				
	-	3	4	Oxic/anoxic		13.00	1.50	0.50	36.00	72	88				
	-	3	4	Oxic/anoxic	-	15.00	4.50	0.50	3.00	6	70				
20	Fox et al., 2006	Soil column	Silica sand	-	-	anoxic	-	8.61	6.08	-	1.00	≤3	29		
							-	8.61	4.10	-	4.00	≤10	52		
21	Rice and Bouwer, 1984	Field study	Sandy loam	-	-	Oxic	-	19.00	6.00	-	0.46-0.56	≤3	68		
		Soil column	Sandy loam			Oxic/anoxic	-	15.00	7.00		2.5	Months	53		

APPENDIX G: Removal of ammonia from secondary effluents by soil column and field SAT systems under different operating conditions

SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature (°C)	Influent NH ₄ -N (mg/L)	effluent NH ₄ -N (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
1	Kanarek and Michail, 1996	Field study	sandy soils	1	2-3	Oxic/anoxic	-	14.90	0.10	-	350-1500	Months	99.33
		Field study	sandy soils	2	2-4	Oxic/anoxic	-	10.36	0.02	-	350-1500	Months	99.81
2	Miller <i>et al.</i> , 2006	Field study	sand and gravel overlain by alluvium	2-4	4	Oxic	-	15.00-20.00	0.5-2.0		0.30	≤day	92.85
3	Cha et al., 2005	Soil columns	Poorly graded sand	4	3	Oxic	20	12.30	2.90	1.34	1.00	1.00	76.42
			Poorly graded sand	4	3	Oxic	20	8.30	3.40	1.34	1.00	1.00	59.04
4	Leach and Enfield, 1983	Soil columns	Konawa sand	7	-	Oxic	13-17	12.90	10.70	0.76	0.25	0.33	17.05
			Konawa sand	7	-	Oxic	13-17	12.90	2.80	0.76	0.7	0.92	78.29
			Konawa sand	7	-	Oxic	13-17	12.90	6.40	0.76	1.30	1.71	50.39
			Konawa sand	7	-	Anoxic	13-17	12.90	8.40	0.76	2.05	2.70	34.88
			Konawa sand	7	-	Anoxic	13-17	12.90	6.00	0.76	2.2	2.89	53.49
			gravelly sand clay	7	-	Oxic	13-17	12.90	12.90	0.84	0.25	0.30	0.00
			gravelly sand clay	7	-	Oxic	13-17	12.90	9.40	0.84	0.7	0.83	27.13
			gravelly sand clay	7	-	Oxic	13-17	12.90	6.30	0.84	1.30	1.55	51.16
			gravelly sand clay	7	-	Anoxic	13-17	12.90	1.00	0.84	2.05	2.44	92.25
			gravelly sand clay	7	-	Anoxic	13-17	12.90	2.40	0.84	2.2	2.62	81.40
5	Leach and Enfield, 1983	Soil columns	Konawa sandy	10	-	Oxic	13-17	4.90	8.20	0.76	0.25	0.33	-67.35
			Konawa sand	10	-	Oxic	13-17	4.90	0.80	0.76	0.7	0.92	83.67
			Konawa sand	10	-	Oxic	13-17	4.90	2.60	0.76	1.30	1.71	46.94
			Konawa sand	10	-	Anoxic	13-17	4.90	5.50	0.76	2.05	2.70	-12.24
			Konawa sand	10	-	Anoxic	13-17	4.90	7.00	0.76	2.2	2.89	-42.86
			gravelly sand clay	10	-	Oxic	13-17	4.90	7.70	0.55	0.25	0.45	-57.14
			gravelly sand clay	10	-	Oxic	13-17	4.90	7.50	0.55	0.7	1.27	-53.06

Negative sign means ammonia is leached

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SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature (°C)	Influent NH ₄ -N (mg/L)	effluent NH ₄ -N (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
5	Leach and Enfield, 1983	Soil columns	gravelly sand clay	10	-	Oxic	13-17	4.90	5.30	0.55	1.30	2.36	-8.16
			gravelly sand clay	10	-	Anoxic	13-17	4.90	4.40	0.55	2.05	3.73	10.20
			gravelly sand clay	10	-	Anoxic	13-17	4.90	4.40	0.55	2.2	4.00	10.20
			Konawa sand	17	-	Oxic	13-17	11.80	0.50	0.55	0.25	0.45	95.76
			Konawa sandy	17	-	Oxic	13-17	11.80	0.09	0.55	0.7	1.27	99.24
			Konawa sand	17	-	Oxic	13-17	11.80	0.10	0.55	1.30	2.36	99.15
			Konawa sand	17	-	Anoxic	13-17	11.80	0.60	0.55	2.05	3.73	95.00
			Konawa sand	17	-	Anoxic	13-17	11.80	7.30	0.55	2.2	4.00	38.14
			gravelly sand clay	17	-	Oxic	13-17	11.80	6.00	0.46	0.25	0.54	49.15
			gravelly sand clay	17	-	Oxic	13-17	11.80	1.80	0.46	0.7	1.52	84.75
			gravelly sand clay	17	-	Oxic	13-17	11.80	9.40	0.46	1.30	2.83	20.34
			gravelly sand clay	17	-	Anoxic	13-17	11.80	4.00	0.46	2.05	4.46	66.10
			gravelly sand clay	17	-	Anoxic	13-17	11.80	6.10	0.46	2.2	4.78	48.31
6	Idolevitch and Michail, 1984	Field study	sand stone	1	2-3	Oxic/anoxic	-	5.00	0.01	1.50-2.00	1020	290	99.80
7	Kanarek <i>et al.</i> , 1993	Field study	Sandy soil	1	2-3	Oxic/anoxic	-	7.56	0.04		350-1500	Months	99.47
8	Castillo <i>et al.</i> , 2001	Soil columnn	Lomey sand	7-21	7-14	Oxic	-	60.00	5	0.03-0.06	1.00	20	91.67
		Soil columnn	Sandy lime	7-21	7-14	Oxic/anoxic	-	60.00	20	0.20-0.40	2.00	7	66.67
9	Diab and Shilo, 1988	Field study	Sandy soil	1	2	Oxic	21.6	6.00	0.02	-	-	Months	99.67
10	Rice and Bouwer, 1984	Field study	-	-	-	Oxic	-	28.00	6.00	-	0.51	≤day	78.57
11	Fox <i>et al.</i> , 2001b	Field study	clay lenses	-	-	Oxic	-	19.00	1.00	0.50	0.3	0.60	95
				-	-	Oxic	-	18.00	1.00	0.50	1	2.00	94
				-	-	Oxic	-	18.00	1.00	0.50	3	6.00	94
				-	-	Oxic	-	18.00	1.00	0.50	6	12.00	94
				-	-	Oxic	-	18.00	1.00	0.50	9	18.00	94
				-	-	Oxic	-	18.00	1.00	0.50	12	24.00	94
				-	-	Oxic	-	18.00	1.00	0.50	15	30.00	94
				-	-	Oxic	-	18.00	1.00	0.50	18	36.00	94

Negative sign means ammonia is leached

APPENDIX H: Removal of nitrate from secondary effluents by soil column and field SAT systems under different operating conditions

SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature (°C)	Influent NO ₃ -N (mg/L)	effluent NO ₃ -N (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
1	Cha et al., 2005	Soil columns	Poorly graded sand	4	3	Oxic	20	5.80	10.10	1.34	1.00	1.00	-74
			Poorly graded sand	4	3	Oxic	20	6.90	6.40	1.34	1.00	1.00	7
2	Leach and Enfield, 1983	Soil columns	Konawa sand	7	-	Oxic	13-17	3.50	3.40	0.76	0.25	0.33	3
			Konawa sand	7	-	Oxic	13-17	3.50	21.70	0.76	0.70	0.92	-520
			Konawa sand	7	-	Oxic	13-17	3.50	26.20	0.76	1.30	1.71	-649
			Konawa sand	7	-	Anoxic	13-17	3.50	20.30	0.76	2.05	2.70	-480
			Konawa sand	7	-	Anoxic	13-17	3.50	12.90	0.76	2.20	2.89	-269
			gravelly sand clay	7	-	Oxic	13-17	3.50	1.00	0.84	0.25	0.30	71
			gravelly sand clay	7	-	Oxic	13-17	3.50	1.00	0.84	0.70	0.83	71
			gravelly sand clay	7	-	Oxic	13-17	3.50	2.00	0.84	1.30	1.55	43
			gravelly sand clay	7	-	Anoxic	13-17	3.50	1.30	0.84	2.05	2.44	63
			gravelly sand clay	7	-	Anoxic	13-17	3.50	1.10	0.84	2.20	2.62	69
			Konawa sand	10	-	Oxic	13-17	3.90	1.10	0.76	0.25	0.33	72
			Konawa sand	10	-	Oxic	13-17	3.90	4.00	0.76	0.70	0.92	-3
			Konawa sand	10	-	Oxic	13-17	3.90	7.30	0.76	1.30	1.71	-87
			Konawa sand	10	-	Anoxic	13-17	3.90	13.80	0.76	2.05	2.70	-254
			Konawa sand	10	-	Anoxic	13-17	3.90	7.30	0.76	2.20	2.89	-87
			gravelly sand clay	10	-	Oxic	13-17	3.90	0.50	0.55	0.25	0.45	87
			gravelly sand clay	10	-	Oxic	13-17	3.90	0.40	0.55	0.70	1.27	90
			gravelly sand clay	10	-	Oxic	13-17	3.90	0.70	0.55	1.30	2.36	82
gravelly sand clay	10	-	Anoxic	13-17	3.90	0.50	0.55	2.05	3.73	87			
gravelly sand clay	10	-	Anoxic	13-17	3.90	0.50	0.55	2.20	4.00	87			
Konagawa sandy	17	-	Oxic	13-17	4.60	9.00	0.55	0.25	0.45	-96			

Negative sign means nitrate is produced

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SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature (°C)	Influent NO ₃ -N (mg/L)	effluent NO ₃ -N (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
2	Leach and Enfield, 1983	Soil columns	Konagawa sandy	17	-	Oxic	13-17	4.60	12.30	0.55	0.70	1.27	-167
			Konagawa sandy	17	-	Oxic	13-17	4.60	20.30	0.55	1.30	2.36	-341
			Konagawa sandy	17	-	Anoxic	13-17	4.60	5.90	0.55	2.05	3.73	-28
			Konagawa sandy	17	-	Anoxic	13-17	4.60	5.30	0.55	2.20	4.00	-15
			gravelly sand clay	17	-	Oxic	13-17	4.60	2.30	0.46	0.25	0.54	50
			gravelly sand clay	17	-	Oxic	13-17	4.60	11.30	0.46	0.70	1.52	-146
			gravelly sand clay	17	-	Oxic	13-17	4.60	6.60	0.46	1.30	2.83	-43
			gravelly sand clay	17	-	Anoxic	13-17	4.60	8.40	0.46	2.05	4.46	-83
			gravelly sand clay	17	-	Anoxic	13-17	4.60	7.20	0.46	2.20	4.78	-57
3	Idolevitch and Michail, 1984	Field study	sand stone	1	2-3	Oxic/anoxic	-	0.10	6.50	1.50-2.00	1020	-	-640
4	Kanarek <i>et al.</i> , 1993	Field study	Sandy soil	1	2-3	Oxic/anoxic	-	2.97	7.17	-	350-1500	-	-141
		Soil column	Sandy lime	7-21	7-14	Oxic/anoxic	-	0.00	10	0.3	2.00	7	-
6	Diab and Shilo, 1988	Field study	Sandy soil	1	2	Oxic	21.6	0.20	8.50	-	-	-	-4150
7	Fox <i>et al.</i> , 2006	Soil columnn	Poorly graded silty sand	-	-	Anoxic	-	30.00	15.00	0.18	0.91	5	50
8	Fox <i>et al.</i> , 2001b	Field study	clay lenses	-	-	Oxic	-	8.00	700.00	0.50	1	2.00	-8650
				-	-	Oxic	-	8.00	100.00	0.50	3	6.00	-1150
				-	-	Oxic	-	8.00	100.00	0.50	1	2.00	-1150
				-	-	Oxic	-	8.00	50.00	0.50	3	6.00	-525
				-	-	Oxic	-	8.00	5.00	0.50	12	24.00	38
				-	-	Oxic	-	8.00	9.00	0.50	24	48.00	-13
				-	-	Oxic	-	8.00	7.00	0.50	38	76.00	13
				-	-	Oxic	-	8.00	120.00	0.50	1	2.00	-1400
				-	-	Oxic	-	8.00	125.00	0.50	3	6.00	-1463
				-	-	Oxic	-	8.00	20.00	0.50	15	30.00	-150
				-	-	Oxic	-	8.00	7.00	0.50	23	46.00	13
				-	-	Oxic	-	8.00	5.00	0.50	30	60.00	38

Negative sign means nitrate is produced

APPENDIX I: Removal of phosphorus from secondary effluents by soil column and field SAT systems under different operating conditions

SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature (°C)	Influent PO ₄ -P (mg/L)	effluent PO ₄ -P (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
1	Idolevitch et al., 2003	Field study	Sandy soils	-	-	Oxic/anoxic	-	3.00-10.00	0.01-0.03	0.50	250-300	Months	99.00
2	Lance <i>et al.</i> , 1980	Soil column	Loamy sand	9	5	Oxic/anoxic	22-25	12.10	4.1	0.21	2.75	13.10	58.00-73.00
3	Kanarek and Michail, 1996	Field study	sandy soils	1	2-3	Oxic/anoxic	-	6.10	0.02	-	350-1500	Months	>99.00
			sandy soils	2	2-4	Oxic/anoxic	-	3.30	0.01	-	350-1500	Months	>99.01
4	Idolevitch and Michail, 1984	Field study	sand stone	1	2-3	Oxic/anoxic	-	2.10	0.03	1.50-2.00	1020	290	98.60
5	Crites, 1985	Field study	-	-	-	Oxic/anoxic	-	5.50	0.37	0.5	30	60	93.00
			-	-	-	Oxic/anoxic	-	3.50	0.03	-	1708	Months	99.00
			-	-	-	Oxic/anoxic	-	2.10	0.03	-	152	Months	99.00
			-	-	-	Oxic/anoxic	-	9.00	0.10	0.5	45	90	99.00
			-	-	-	Oxic/anoxic	-	2.10	0.01	-	610	Months	99.00
6	Kanarek <i>et al.</i> , 1993	Field study	Sandy soil	1	2-3	Oxic/anoxic	-	3.40	0.02	-	350-1500	Months	99.40

APPENDIX J: Removal of trace organics from secondary effluents by soil column and field SAT systems under different operating conditions

SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature (°C)	Trace organic type and concentration Unit	Influent concentration	effluent concentration	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
1	Yoo <i>et al.</i> , 2006	Field study	Poorly graded silty sand	3	4	Oxic/anoxic	-	EDTA (µg/L)	26.90	33.90	2.00	3.00	1-2	-26.00
								EDTA (µg/L)	26.90	4.20	2.00	38.00	-	84.00
								EDTA (µg/L)	24.60	30.40	2.00	3.00	1-2	-24.00
								EDTA (µg/L)	24.60	5.00	2.00	38.00	-	80.00
								NTA (µg/L)	4.10	0.40	2.00	3.00	1-2	90.00
								NTA (µg/L)	4.10	0.10	2.00	38.00	-	98.00
								NTA (µg/L)	4.80	2.10	2.00	3.00	-	56.00
								NTA (µg/L)	4.80	0.50	2.00	38.00	-	90.00
								APEC (µg/L)	64.80	40.50	2.00	3.00	1-2	37.00
								APEC (µg/L)	64.80	0.60	2.00	38.00	-	99.00
								APEC (µg/L)	61.50	46.60	2.00	3.00	1-2	24.00
								APEC (µg/L)	61.50	1.50	2.00	38.00	-	98.00
2	Fox <i>et al.</i> , 2001b	Field study	Poorly graded silty sand	3	4	Oxic/anoxic	-	EDTA (µg/L)	34.00	26.00	-	24.00	-	24.00
								NTA (µg/L)	5.70	0.50	-	24.00	-	91.00
								APEC (µg/L)	75.00	7.00	-	24.00	-	91.00
								NDC (µg/L)	25.00	5.00	-	24.00	-	80.00
								EDTA (µg/L)	25.00	42.00	-	3.00	-	-68.00
								NTA (µg/L)	4.00	1.00	-	3.00	-	75.00
								APEC (µg/L)	60.00	35.00	-	3.00	-	42.00
								NDC (µg/L)	25.00	5.00	-	3.00	-	80.00
								EDTA (µg/L)	8.00	2.50	-	22.50	-	69.00
								NTA (µg/L)	1.70	0.00	-	22.50	-	100.00
								APEC (µg/L)	40.00	3	-	22.50	-	92.00
								NDC (µg/L)	2.00	1.00	-	22.50	-	50.00
3	Tomson <i>et al.</i> , 1981	Field study	-	-	-	Oxic/anoxic	-	Chloroalkanes (Tetrachloroethylene) (µg/L)	0.19	0.06	-	18.2	-	70.00
			-	-	-	-	Chloroaromatics (p-dichlorobenzene) (µg/L)	0.92	0.06	-	18.2	-	94.00	
			-	-	-	-	Alkylbenzene (o-xylene) (µg/L)	5.93	0.12	-	18.2	-	98.00	
			-	-	-	-	Alkylphenol (p-isopropylphenol) (µg/L)	1.62	0.24	-	18.2	-	85.00	
			-	-	-	-	Alkyl naphthalenes (2-methylnaphthalenes) (µg/L)	2.10	0.00	-	18.2	-	100.00	
			-	-	-	-	Alkanes (hexatriacontane) (µg/L)	0.67	0.19	-	18.2	-	71.00	
			-	-	-	-	Alcohols (2,4 dimethyl-3-hexanol) (µg/L)	0.13	0.006	-	18.2	-	95.00	

Negative sign means a trace organic is leached

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SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature (°C)	Trace organic type and concentration Unit	Influent concentration	effluent concentration	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
3	Tomson <i>et al.</i> , 1981	Field study	-	-	-	Oxic/anoxic	-	Ketones (2,6 di-t-butyl-p-benzoquinone) (µg/L)	0.20	0.004	-	18.2	-	98.00
			-	-	-	Oxic/anoxic	-	Phthaletes (dibutylphthalete) (µg/L)	0.39	0.379	-	18.2	-	2.00
			-	-	-	Oxic/anoxic	-	Indole, Indenes (IH-indole) (µg/L)	1.74	0.071	-	18.2	-	96.00
			-	-	-	Oxic/anoxic	-	Amides (N-[3-methlyphenyl] acetamide) (µg/L)	0.21	0.055	-	18.2	-	74.00
			-	-	-	Oxic/anoxic	-	Alkoxyaromatics (butoxymethylbenzene) (µg/L)	0.11	0.010	-	18.2	-	76.00
4	Bouwer <i>et al.</i> , 1981	Soil column	Loamy sand	9	5	Oxic/anoxic	-	1,3-dichlorobenzene (µg/L)	0.12	35	0.42, 0.28, 0.24	2.75	9	71.00
								1,4-dichlorobenzene (µg/L)	0.82	120	0.42, 0.28, 0.24	2.75	9	85.00
								1,2-dichlorobenzene (µg/L)	0.76	105	0.42, 0.28, 0.24	2.75	9	86.00
								cadenine (µg/L)	0.15	30	0.42, 0.28, 0.24	2.75	9	80.00
								1,4-cineol (µg/L)	1.20	0.00	0.42, 0.28, 0.24	2.75	9	100.00
								1,2,4-trichlorobenzene(µg/L))	0.21	0.00	0.42, 0.28, 0.24	2.75	9	100.00
								Neoisothujyl alcohol (µg/L)	0.21	0.00	0.42, 0.28, 0.24	2.75	9	100.00
								2,3,4,5-tetrachloroanisole (ng/L)	15.00	15.00	0.42, 0.28, 0.24	2.75	9	0.00
								Pentachloroanisole (ng/L)	70.00	40.00	0.42, 0.28, 0.24	2.75	9	43.00
								Lindane (ng/L)	90.00	15.00	0.42, 0.28, 0.24	2.75	9	83.00
								Diisobutyle phthalate (ng/L)	40.00	20.00	0.42, 0.28, 0.24	2.75	9	50.00
								DDT (ng/L)	40.00	40.00	0.42, 0.28, 0.24	2.75	9	0.00
								Diethyl phthalate (ng/L)	70.00	130.00	0.42, 0.28, 0.24	2.75	9	-86.00
di-n-butyl phthalate (ng/L)	110.00	15.00	0.42, 0.28, 0.24	2.75	9	86.00								
Alkylated phenol (ng/L)	230.00	70.00	0.42, 0.28, 0.24	2.75	9	70.00								

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S/N	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature (°C)	Trace organic type and concentration Unit	Influent concentration	effluent concentration	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
4	Bouwer et al., 1981							2,3,5,6-tetrachloroanisole (ng/L)	110.00	0.00	0.42, 0.28, 0.24	2.75	9	100.00
5	Fox et al., 2006	Soil column	Silica sand	-	-	Oxic	-	EDC-17 β-estradiol (ng/L)	200.00	0.002	1.20	0.30	0.25	99.00
								EDC-estriol (ng/L)	200.00	0.00	1.20	0.30	0.25	100.00
								EDC-testosterone (ng/L)	200.00	0.00	1.20	0.30	0.25	100.00
								Anoxic	EDC-17 β-estradiol (ng/L)	285.00	1.10	-	1.00	-
						EDC-17 β-estradiol (ng/L)		285.00	0.30	-	4.00	-	99.90	
						EDC-estriol (ng/L)		161.00	0.50	-	1.00	-	99.70	
						EDC-estriol (ng/L)		161.00	0.50	-	4.00	-	99.70	
						EDC-testosterone (ng/L)		218.00	0.40	-	1.00	-	99.80	
		EDC-testosterone (ng/L)	218.00	0.40	-	4.00	-	99.80						
		Field study	Gravel,sand silt	-	-	Oxic/anoxic	-	PhaC-Carbamezapine (ng/L)	0.00	610.00	-	39.00		
Oxic/anoxic	PhaC-Primidone (ng/L)					110.00		155.00	-	39.00		-41.00		
6	Mansell et al., 2004	Soil column	Silica sand	-	-	Oxic	-	EDC-17 β-estradiol (µg/L)	0.20	0.002	1.20	0.30	0.25	99.00
								EDC-estriol (µg/L)	0.20	0.00	1.20	0.30	0.25	100.00
								EDC-testosterone (µg/L)	0.20	0.00	1.20	0.30	0.25	100.00
7	Drewes et al., 2002	Field study	Gravel,sand silt	-	-	Oxic/anoxic	-	PhaC-Gemfibrozil (ng/L)	1235.00	0.00	-	39.00		100.00
						Oxic/anoxic		PhaC-Carbamazepine (ng/L)	0.00	610.00	-	39.00		-
						Oxic/anoxic		PhaC-Primidone (ng/L)	110.00	155.00	-	39.00		-41.00
						Oxic/anoxic		PhaC-Diclofenac (ng/L)	80.00	0.00	-	39.00		100.00
						Oxic/anoxic		PhaC-Ibuprofen (ng/L)	3380.00	0.00	-	39.00		100.00
						Oxic/anoxic		PhaC-Ketoprofen (ng/L)	45.00	0.00	-	39.00		100.00
						Oxic/anoxic		PhaC-Naproxen (ng/L)	6280.00	<10	-	39.00		>99.99
						Oxic/anoxic		PhaC-Fenoprofen (ng/L)	35.00	0.00	-	39.00		100.00
Oxic/anoxic	PhaC-Propyphenazone (ng/L)	20.00	0.00	-	39.00		100.00							

APPENDIX K: Removal of microbes from secondary effluent by soil column and field SAT systems under different operating conditions

SN	Litreature source	Study/ Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater Temperature (°C)	Microbe name (unit)	Influent	effluent	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Log removal
1	Idolevitch and Michail, 1984	Field study	sand stone	1	2-3	Oxic/anoxic	-	Total coliform (MPN/100ml)	400.00	0-20	1.50-2.00	1020	-	1.60
								E.Coli (MPN/100ml)	50.00	0				No detection
								S.Faecalis (MPN/100ml)	150.00	0				No detection
2	Kanarek <i>et al.</i> , 1993	Field study	Sandy soil	1	2-3	Oxic/anoxic	-	Total coliform (MPN/100ml)	1100000.00	0.00	-	350-1500	-	No detection
								E. Coli (MPN/100ml)	130000.00	0.00				No detection
								Streptococcus Faecalis (MPN/100ml)	29000.00	0.00				No detection
3	Rice and Bouwer, 1984	Field study	-	-	-	Oxic	-	Total coliform (MPN/100ml)	2500000	0-100		0.46-0.56		4.60
4	Castillo <i>et al.</i> , 2001	Soil columns	Limey sand	7-21	7-14	Oxic	-	Faecal coliform (MPN/100ml)	10000000.00	6	0.03-0.06	1.00	20	6.20
			Sandy lime	7-21	7-14	Oxic/anoxic	-	Faecal coliform (MPN/100ml)	10000000.00	200	0.20-0.40	2.00	7	4.50
			Limey sand	7-21	7-14	Oxic	-	MS2 phage (pfu)	10000.00	20	0.03-0.06	1.00	20	2.50
			Sandy lime	7-21	7-14	Oxic	-	MS2 phage (pfu)	10000.00	200	0.20-0.40	2.00	7	1.50
			Sandy lime	7-21	7-14	Oxic	-	Giardia cysts/L	12	0	0.20-0.40	2.00	7	No detection
			Sandy lime	7-21	7-14	Oxic	-	Salmonella spp	100000.00	1000	0.20-0.40	2.00	7	3.00
5	Powelson <i>et al.</i> , 1993	Field study	Gravel, sand and clay	7	7	Oxic		MS2 Virus (pfu)	-	-	11.00	1.00	0.09	0.00
						Oxic		MS2 Virus (pfu)	-	-	11.00	2.00	0.18	0.00
						Oxic/anoxic		MS2 Virus (pfu)	-	-	11.00	3.00	0.27	0.10
						Oxic/anoxic		MS2 Virus (pfu)	-	-	11.00	4.00	0.36	0.40
						Oxic/anoxic		MS2 Virus (pfu)	-	-	11.00	5.00	0.45	0.60
						Oxic	30.00	MS2 Virus (pfu)	-	-	0.80	1.00	1.25	0.80
						Oxic	30.00	MS2 Virus (pfu)	-	-	0.80	2.00	2.50	2.70
						Oxic/anoxic	30.00	MS2 Virus (pfu)	-	-	0.80	3.00	3.75	1.20
						Oxic/anoxic	30.00	MS2 Virus (pfu)	-	-	0.80	4.00	5.00	1.30
						Oxic/anoxic	30.00	MS2 Virus (pfu)	-	-	0.80	5.00	6.25	4.00
						Oxic		MS2 Virus (pfu)	-	-	1.00	1.00	1.00	0.90
						Oxic		MS2 Virus (pfu)	-	-	1.00	2.00	2.00	1.40
						Oxic/anoxic		MS2 Virus (pfu)	-	-	1.00	3.00	3.00	0.97
						Oxic/anoxic		MS2 Virus (pfu)	-	-	1.00	4.00	4.00	1.50
Oxic/anoxic		MS2 Virus (pfu)	-	-	1.00	5.00	5.00	2.87						

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SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater Temperature (°C)	Microbe name (unit)	Influent	effluent	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Log removal
5	Powelson et al., 1993	Field study	Gravel, sand and clay	7	7	Oxic		PRDI virus (pfu)	-	-	11.00	1.00	0.09	0.40
						Oxic		PRDI virus (pfu)	-	-	11.00	2.00	0.18	1.80
						Oxic/anoxic		PRDI virus (pfu)	-	-	11.00	3.00	0.27	1.20
						Oxic/anoxic		PRDI virus (pfu)	-	-	11.00	4.00	0.36	1.50
						Oxic/anoxic		PRDI virus (pfu)	-	-	11.00	5.00	0.45	2.00
						Oxic	30.00	PRDI virus (pfu)	-	-	0.80	1.00	1.25	2.00
						Oxic	30.00	PRDI virus (pfu)	-	-	0.80	2.00	2.50	3.60
						Oxic/anoxic	30.00	PRDI virus (pfu)	-	-	0.80	3.00	3.75	3.30
						Oxic/anoxic	30.00	PRDI virus (pfu)	-	-	0.80	4.00	5.00	2.50
						Oxic/anoxic	30.00	PRDI virus (pfu)	-	-	0.80	5.00	6.25	4.00
						Oxic		PRDI virus (pfu)	-	-	1.00	1.00	1.00	4.00
						Oxic		PRDI virus (pfu)	-	-	1.00	2.00	2.00	3.00
						Oxic/anoxic		PRDI virus (pfu)	-	-	1.00	3.00	3.00	2.50
						Oxic/anoxic		PRDI virus (pfu)	-	-	1.00	4.00	4.00	1.80
Oxic/anoxic		PRDI virus (pfu)	-	-	1.00	5.00	5.00	4.00						
6	Quanrud et al., 2003b	Soil column	Sandy loam	7	7	Oxic	Eff temp 25	Coliphage (pfu)	21200000.00	1900000.00	1.40	1.00	0.71	1.00
			Poorly graded sand	7	7	Oxic	Eff temp 25	Coliphage (pfu)	5900000.00	1600000.00	1.20	1.00	0.83	0.56
			Silica sand	7	7	Oxic	Eff temp 25	Polio virus type 1(pfu)	22500000.00	2500000.00	1.20	1.00	0.83	0.95

APPENDIX L: Removal of DOC from tertiary effluent by batch, soil column and field SAT systems under different operating conditions

SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature (°C)	Influent DOC (mg/L)	effluent DOC (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
1	Reemtsma et al., 2000	Soil column	Quartz sand	-	-		.	16.67	12.00	0.2	1.80	9.0	28.00
		Field study	loamy sand	-	-	Oxic/anoxic	-	16.20	9.00	0.1	19.70	19.7	44.00
2	Quanrud et al., 1996a	Soil column	Loamy soil	7	7	Oxic	24-26	8.00	4.80	0.90	1.00	1	40.00
3	Fox et al., 2001a	Field study	Fine clay	-	-	Oxic	-	5.00-7.00	3.00	0.06-0.12	1.50	2	50.00
				-	-	Anoxic	-	5.00-7.00	1.42	0.90	28.50	32	76.00
4	Amy and Drewes, 2006a	Field study	-	-	-	Oxic/anoxic	-	6.10	1.47	-	418	-	76.00
5	Cha et al., 2004b	Batch reactors	Sandy soil	-	-	Oxic	23-25	10.00	6.40	-	N/A	30	36.00
		Batch reactors	Sandy soil	-	-	Oxic	23-25	15.00	9.50	-	N/A	30	37.00
		Batch reactors	Sandy soil	-	-	Oxic	23-25	24.00	14.70	-	N/A	30	39.00
6	Jarusutthirak et al., 2003	Field study	-	-	-	Oxic/anoxic	-	5.71	1.12	-	235	180	80.00
7	Quanrud et al., 1996a	Soil column	loamy soil	7	7	Oxic	24-26	9.35	6.50	0.90	1.00	1	30.00
8	Drewes and Jekel, 1996	Soil column	sand (grain size 1-2 mm)	-	-	Oxic	-	13.60	10-11	-	2.00	2	23.00
9	Drewes and Jekel, 1998	Soil column	sand (grain size 1-2 mm)	-	-	Oxic	-	16.40	13.60	0.13	2.00	15	17.00
		Soil column	sand (grain size 1-2 mm)	-	-	Oxic	-	16.41	12.36	0.13	2.00	15	25.00
		Soil column	sand (grain size 1-2 mm)	-	-	Oxic	-	17.50	11.67	0.10	2.00	20	33.00
		Soil column	sand (grain size 1-2 mm)	-	-	Oxic	-	14.73	10.10	0.13	2.00	15	31.00
10	Drewes et al., 2003	Field study	-	-	-	Oxic/anoxic	-	5.64	1.23	-	-	360-540	78.00
11	Fox et al., 2006	Field study	clay, sand, silty	-	-	Oxic	-	6.74	5.20	-	1.50	<10	23.00
				-	-	Oxic/anoxic	-	6.74	1.47	-	905.00	540	78.00
12	Yun-Zheng and Jian-long, 2006	Field study	sandy loam	6-8	10-14	Oxic/anoxic	-	4.90	2.3	-	9	<20	53.00
				-	-	Oxic/anoxic	-	4.90	2.1	-	52	Months	57.00
13	Wilson et al., 1995	Field study	clay, sand, silty	5	7	Oxic	-	19.40	7.76	1.27	0.8	0.63	60.00
						Oxic/anoxic	-	19.40	8.15	1.27	3.10	2.44	58.00
						Oxic/anoxic	-	19.40	5.82	1.27	5.20	4.09	70.00
						Oxic/anoxic	-	19.40	4.85	1.27	24.4	19.21	75.00
						Oxic	-	12.00	3.36	1.00	0.80	0.80	72.00
						Oxic/anoxic	-	12.00	5.40	1.00	3.10	3.10	55.00
						Oxic/anoxic	-	12.00	2.16	1.00	12.20	12.20	82.00
Oxic/anoxic	-	12.00	2.40	1.00	24.40	24.40	80.00						

APPENDIX M: Removal of ammonia from tertiary effluent by soil column and field SAT systems under different operating conditions

SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature (°C)	Influent NH ₄ -N (mg/L)	effluent NH ₄ -N (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
1	Reemtsma et al., 2000	Soil column	Quartz sand	-	-		room temp.	2.00	0.00	0.20	1.80	9	100.00
		Field study	loamy sand	-	-	oxic	-	1.50	0.23	0.10	1.20	12	85.00
2	Viswanathan et al., 1999	Field study	fine-course sand layers	0.5	0.5	Oxic/anoxic	31-49	8.50	0.00	0.76	29.00	38.16	100.00

APPENDIX N: Removal of nitrate from tertiary effluent by soil column and field SAT systems under different operating conditions

SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature (°C)	Influent NO ₃ -N (mg/L)	effluent NO ₃ -N (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
1	Reemtsma et al., 2000	Field study	loamy sand	-	-	oxic/anoxic	-	5.80	16.00	0.10	19.70	197	-176.00
		Soil column	Quartz sand	-	-	oxic/anoxic	-	5.80	9.00	0.20	1.80	9	-55.00
2	Viswanathan et al., 1999	Field study	fine-course sand layers	0.5	0.5	Oxic/anoxic	31-49	4.70	3.70	0.76	29.00	38.16	21.00

Negative sign means nitrate is produced

APPENDIX O: Removal of phosphorus from tertiary effluent by soil column and field SAT systems under different operating conditions

SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature (°C)	Influent PO ₄ -P (mg/L)	effluent PO ₄ -P (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
1	Reemtsma et al., 2000	Field study	loamy sand	-	-	oxic	-	0.16	2.10	0.10	19.70	197	-1200.00
		Soil column	Quartz sand	-	-		room temp.	0.16	0.10	0.20	1.80	9	37.00
2	Viswanathan et al., 1999	Field study	fine-course sand layers	0.5	0.5	Oxic/anoxic	31-49	16.20	3.30	0.76	29.00	38.16	80.00

Negative sign means phosphorus is leached

APPENDIX P: Removal of trace organics from tertiary effluent by field SAT systems under different operating conditions

SN	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature (°C)	Trace organic type and concentration Unit	Influent concentration	effluent concentration	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Removal efficiency (%)
1	Fox et al., 2001b	Field study	Poorly graded silty sand	-	-	Oxic/anoxic	-	EDTA (µg/L)	29.00	4.30	-	390.00	180-540	85
				-	-	Oxic/anoxic	-	NTA (µg/L)	0.60	0.00	-	390.00	180-540	100
				-	-	Oxic/anoxic	-	APEC (µg/L)	48.00	0.90	-	390.00	180-540	98
				-	-	Oxic/anoxic	-	NDC (µg/L)	6.90	0.60	-	390.00	180-540	91
2	Montgomery-Brown <i>et al.</i> , 2003	Field study	Gravel, sand and silts	7	21	Oxic/anoxic	11.6-29.4	APEC (µg/L)	22.20	1.00	0.09	3.00	8-14	95
				7	21	Oxic/anoxic	11.6-29.4	APEC (µg/L)	22.20	Traces	-	903.00	360-540	100
				7	21	Oxic/anoxic	11.6-29.4	CAPEC (µg/L)	28.00	0.07	0.09	3.00	8-14	99.7
				7	21	Oxic/anoxic	11.6-29.4	CAPEC (µg/L)	28.00	Traces	-	903.00	360-540	100
3	Fox et al., 2006	Field study	clay,sand,silt	-	-	Oxic	-	EDC-17 β-estradiol (ng/L)	4.20	0.50	-	1.50	-	88.00
				-	-	Oxic/anoxic	-	EDC-17 β-estradiol (ng/L)	4.20	0.30	-	905.00	>540	93.00
				-	-	Oxic	-	EDC-estriol (ng/L)	4.90	0.50	-	1.50	-	90.00
				-	-	Oxic/anoxic	-	EDC-estriol (ng/L)	4.90	0.50	-	905.00	>540	90.00
				-	-	Oxic	-	EDC-testosterone (ng/L)	3.00	0.50	-	1.50	-	83.00
				-	-	Oxic/anoxic	-	EDC-testosterone (ng/L)	3.00	0.50	-	905	>540	83.00
				-	-	Oxic/anoxic	-	PhaC-Carbamazepine (ng/L)	155.00	125.00	-	905	>540	19.00
4	Drewes et al., 2003	Field study	clay,sand,silt	-	-	Oxic/anoxic	-	EDTA (µg/L)	34.50	3.95	-	905.00	>540	89
				-	-	Oxic/anoxic	-	NTA (µg/L)	0.80	0.00	-	905.00	>540	100

APPENDIX Q: Removal of microbes from tertiary effluent by field SAT systems under different operating conditions

S/N	Litreature source	Study/Experiment	Soil type	Wetting period (Days)	Drying period (Days)	Redox conditions	Wastewater temperature (°C)	Microbe name	Unit	Influent	effluent	Infiltration rate (m/day)	Travel distance (m)	Residence time (day)	Log removal
1	Viswanathan <i>et al.</i> , 1999	Field study	fine-course sand layers	0.5	0.5	Oxic/anoxic	31-49	Total Coliform	MPN/100 mL	2.10E+04	8.00E+01	0.76	29.00	38.16	2.42
				1.5	0.6	Oxic/anoxic	31-50	Faecal Coliform	MPN/100 mL	2.86E+02	0.00E+00	0.76	29.00	38.16	ND
2	Powelson <i>et al.</i> , 1993	Field study	Gravel, sand and clay	7	7	Oxic	-	MS2 Virus	pfu/mL	-	-	10.00	1.00	0.10	0.80
						Oxic	-	MS2 Virus	pfu/mL	-	-	10.00	2.00	0.20	0.70
						Oxic/anoxic	-	MS2 Virus	pfu/mL	-	-	10.00	3.00	0.30	0.80
						Oxic/anoxic	-	MS2 Virus	pfu/mL	-	-	10.00	4.00	0.40	0.90
						Oxic/anoxic	-	MS2 Virus	pfu/mL	-	-	10.00	5.00	0.50	2.00
						Oxic	18.00	MS2 Virus	pfu/mL	-	-	2.25	1.00	0.44	0.40
						Oxic	18.00	MS2 Virus	pfu/mL	-	-	2.25	2.00	0.89	0.60
						Oxic/anoxic	18.00	MS2 Virus	pfu/mL	-	-	2.25	3.00	1.33	0.60
						Oxic/anoxic	18.00	MS2 Virus	pfu/mL	-	-	2.25	4.00	1.78	0.50
						Oxic/anoxic	18.00	MS2 Virus	pfu/mL	-	-	2.25	5.00	2.22	3.00
						Oxic	-	MS2 Virus	pfu/mL	-	-	1.10	1.00	0.91	0.60
						Oxic	-	MS2 Virus	pfu/mL	-	-	1.10	2.00	1.82	0.70
						Oxic/anoxic	-	MS2 Virus	pfu/mL	-	-	1.10	3.00	2.73	1.30
						Oxic/anoxic	-	MS2 Virus	pfu/mL	-	-	1.10	4.00	3.64	1.80
						Oxic/anoxic	-	MS2 Virus	pfu/mL	-	-	1.10	5.00	4.55	4.00
						Oxic	-	PRDI virus	pfu/mL	-	-	10.00	1.00	0.10	1.30
						Oxic	-	PRDI virus	pfu/mL	-	-	10.00	2.00	0.20	1.30
						Oxic/anoxic	-	PRDI virus	pfu/mL	-	-	10.00	3.00	0.30	1.10
						Oxic/anoxic	-	PRDI virus	pfu/mL	-	-	10.00	4.00	0.40	1.00
						Oxic/anoxic	-	PRDI virus	pfu/mL	-	-	10.00	5.00	0.50	2.70
						Oxic	18.00	PRDI virus	pfu/mL	-	-	2.25	1.00	0.44	0.90
						Oxic	18.00	PRDI virus	pfu/mL	-	-	2.25	2.00	0.89	1.20
						Oxic/anoxic	18.00	PRDI virus	pfu/mL	-	-	2.25	3.00	1.33	1.10
						Oxic/anoxic	18.00	PRDI virus	pfu/mL	-	-	2.25	4.00	1.78	0.90
Oxic/anoxic	18.00	PRDI virus	pfu/mL	-	-	2.25	5.00	2.22	1.90						
Oxic	-	PRDI virus	pfu/mL	-	-	1.10	1.00	0.91	1.50						
Oxic	-	PRDI virus	pfu/mL	-	-	1.10	2.00	1.82	2.50						
Oxic/anoxic	-	PRDI virus	pfu/mL	-	-	1.10	3.00	2.73	2.90						
Oxic/anoxic	-	PRDI virus	pfu/mL	-	-	1.10	4.00	3.64	2.60						
Oxic/anoxic	-	PRDI virus	pfu/mL	-	-	1.10	5.00	4.55	4.00						

