Reclamation of domestic greywater for agricultural irrigation by intermittent sand filter bioreactor

家庭雑排水の農業再利用のための間欠砂ろ過床法に関する研究

by

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ABSTRACT

Potential adverse effects to human health, environment and purpose-related infrastructure should be considered when designing systems for treatment and reuse of greywater. Intermittent sand filtration (ISF) bioreactors are efficient systems for treatment of wastewater and are able to produce effluents of high quality. However, ISFs have potential to clog easily under uncontrolled loads of solids and organics. Furthermore, the specifications of its design are varied and generally aim to polish effluents for environmental discharge. This study discusses an approach to extend the lifetime of ISFs by incorporating a pretreatment that aims to control the size of solids loaded to the bioreactor and to design the configuration of an ISF based on standards of quality that are suitable to the agriculture reuse scenario.

In Chapter 1, background and the objectives of this study were described. Greywater reuse potential, drawbacks and potential adverse effects were enumerated. Natural treatment technologies were compared and the suitability of intermittent sand filtration bioreactors for some scenarios is discussed. Challenges for an improved setup of these systems are listed.

In Chapter 2, the capability of geotextile fabric filter for removal of SS from greywater and the effects of this system when used as pretreatment for ISFs were investigated. The efficacy of several polypropylene non-woven geotextiles (apparent opening size from 0.10 to 0.18 mm) used as primary treatment filters to remove suspended particles from domestic greywater and the effects of this pretreatment in the performance of fine and small media size (0.3 and 0.6 mm) ISFs was examined. Results showed geotextile achieved suspended solids (SS) removal rates from 25% to 85% and chemical oxygen demand (COD) from 3% to 30%; although the portion larger than 75 μm was removed at higher rates (55% to 90%), particles smaller than the nominal pore size of the filter were also captured. Geotextile used as pretreatment resulted in improvement of lifetime of the ISFs over an experimental run of 60 days. The vertical profile of volatile organic matter in the ISFs was evaluated at the end of the experiment and it showed a clear reduction in the accumulation of organic material on the top layer of the ISFs, effectively avoiding its early failure by accumulation of solids.

In Chapter 3, the influence of media when using a ISF for treating domestic greywater was investigated. The efficiency of the systems to reclaim effluents to be used in agricultural irrigation was evaluated by comparing the impact of physical parameters: depth (0.2, 0.4 and 0.6 m), media size (0.3, 0.6 and 0.9 mm) and layering in the quality of effluent regarding three potential risks: health safety (E. Coli 0-5 log reduction), damage to irrigation systems (SS < 3mg L^{-1} and COD) and phytotoxicity (LAS < 8 mg L^{-1}) indicators. Six ISF configurations were operated for 250 days without clogging or requiring any other maintenance than changing the geotextile filter used as pretreatment. SS and LAS concentrations were below the limits set in all cases, showing that even the shallowest ISF is effective. Removal of

E Coli ranged from 1.2 to 2.2 log, considered not enough to reach an acceptable level for intensive human handling, but sufficient for usage in conjunction with high-efficiency irrigation systems. Depth and inclusion of fine sand layer showed a marginal improvement in the removal of dissolved organic matter in effluent, which can be an advantage to avoid potential biofilm regrowth in irrigation systems.

In Chapter 4, using the same quality parameters previously described, the effects of hydraulic loading rate (HLR) on a stratified 40-cm depth ISF in the effluent of treated greywater were evaluated. HLRs of 8, 16, 32 and 48 cm d^{-1} were used. Increasing of the hydraulic daily discharge (i.e. reduction of surface area) reduced the lifetime of ISFs and marginally reduced the quality of effluent in terms of SS and dissolved organic matter. Although higher SS was observed, it was mostly non-settleable particles, and therefore less likely to cause immediate damage to irrigation systems. In contrast, the total filtering capacity of the systems was higher when greater daily discharges were used. Low removal of E. Coli was observed a maximum of 2 log units under the experimental conditions (8 cm d^{-1}), so additional measures must be considered for safe reuse of LLGW treated by ISF.

In Chapter 5, the efficiency of ISF systems to remove hydrophobic organic micro pollutants was evaluated. Emergent micro pollutants such as UV filters have a potential to bio accumulate in biota or soil due to its hydrophobic characteristics. Four of the most common compounds in the market: p-aminobenzoic acid, benzophenone-3, ethylhexyl methoxycinnamate and octocrylene, were chosen. All of them had different levels of hydrophobicity evaluated by log Kow and the solubility in water. The same six ISFs as in Chapter 3 were used for this experiment. Results showed that ISFs of only 20 cm depth were able to capture the hydrophobic UV filters to concentrations under 0.0005 mg/L (99.95% removal). The form of hydrophobic compounds changed in the greywater phase showed to depend on the solubility of the compound, the nature of the product matrix and the contents of surfactants in greywater. However, hydrophilic UV compounds were removed in lower rates, similar to that of total dissolved organic matter.

In Chapter 6, the results obtained in the previous chapters were applied to designing ISFs for implementation in rural area scenarios. Comparisons were made between different financing scenarios and the cost-effectiveness of the systems was evaluated.

In Chapter 7, the summary of most important findings and conclusions of this research and recommendations for future studies are listed.

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AOS	Apparent opening size
BDOC	Biodegradable organic carbon
BDOC14	Biodegradable organic carbon after 14 days of incubation
BDOC28	Biodegradable organic carbon after 28 days of incubation
BDOC7	Biodegradable organic carbon after 7 days of incubation
BOD	Biochemical oxygen demand
BP3	Benzophenone-3
COD	Chemical oxygen demand
D10	Particle size at which 10% of the material is finer
D60	Particle size at which 60% of the media is finer
E. coli	Escherichia coli
EHMC	Ethylhexyl methoxycinnamate
HLR	Hydraulic loading rate
ISF	Intermittent sand filter
LAS	Linear alkylbenzene sulfonate
NH4+-N	Ammonium nitrogen
NO3⁻-N	Nitrate nitrogen
OC	Octocrylene
OLR	Organic loading rate
PABA	P-aminobenzoic acid
TOC	Total organic carbon
Tot-N	Total nitrogen
Tot-P	Total phosphorus
TSS	Total suspended solids

Chapter 1

INTRODUCTION

1.1 WORLD WATER ISSUES

Water is necessary for human survival and the accessibility to a reliable source of potable water is a basic human right. Water access is necessary for human life and development of society. The current human population and its constant growth pose a large footprint to Earth resources and its future. Overexploitation and misuse has led to issues in availability and quality of water. The demand for this services increases in developing countries, where population continues to grow. Aquifer depletion and polluted surface water can lead to water stress conditions, and furthermore, affect the food security. Particularly, such scenarios can be found in developing countries. Worldwide, nearly 1.8 billion of people face water access issues and 2.8 billion lack of sanitation in present (UN, 2013). The availability of water has a direct effect on the producible food and could be a limiting factor (UN-Water & FAO 2007).

On the other hand, sanitation has been recognized as a human right only since 2010 by United Nations (Resolution 64/292), which involves the access to, and use of excreta and wastewater facilities and services, for human dignity.

1.1.1 The case of Guatemala

Guatemala is a country located in the Central American isthmus, neighboring with Mexico, El Salvador and Honduras. Guatemala has a total area of 108,890 square kilometers and a population of 15.5 million (INE, Guatemala). The capital is Guatemala City, which holds a fixed population of about 2 million inhabitants, but a large daily flux of workers that swells the people that economically depend on the city. Guatemala is among the poorest and less developed countries of Latin America and the World. About 53.7% of the population has been estimated to live in poverty (FAO-Guatemala & MAGA 2012). 13.3% of people live in extreme poverty (2% less than 10 years ago). 47% of people live in the rural area, but the "rurality" of each province varies. In general, 63% of the houses located in rural area are within levels of poverty, while 16% is in extreme poverty. Issues of race and gender still play a role in the economic levels, where indigenous people and women have been recognized as the group with higher risk (WFP, 2012). Chronic under-nutrition rate in rural area reaches 50% of children under 5 years old, which is the highest in the area and 4th highest in the World.

Particularly, in rural area this rate is as high as 69.5%. These conditions have strong detrimental effects on physical and social development (Reurings *et al.* 2013).

As in many developing countries, the focus of investment from government has given priority to water access, but almost none to sanitation. Currently, more than 90% of people has access to a reliable source of water (potable or not), but less than 5% of municipalities provide any wastewater treatment service. Although laws have been enacted for the regulation of water disposal, the reality is that large centralized systems and collecting infrastructure are not affordable under the current conditions. With the current population, its growth and the water consumption patterns, it is estimated that by 2025 the water will start to be scarce in terms of quality, while not in volume.

Figure 1.1 Guatemala *(Source: UN)*

Given the nature of agriculture and livestock activities, it is in the rural area where they are more relevant and according to a census in 2011, 66.8% of people in rural area depend or are involved in this type of labor. Furthermore, the economical profile of these people showed that 77% of agriculture workers live in poverty, being a majority of indigenous people, living in rural area (Cannock & Chumpitaz 2012). This situation correlates with low levels of education and large families, as well as the limited levels of income. This is reflected also in the quality of life, with dwellings characterized by being made with precarious materials and low access to infrastructure services. 53% of houses have no constructed floor (directly over the ground) and only 14% has some type of sewage.

Albeit such a large number of people are employed in agriculture, the levels of productivity are low and most of the benefits go to large commercial producers, who can afford technology and better yields while lowering costs and employing workers with low wages. Leaving aside the large commercial producers, the land ownership in Guatemala follows a trend of smaller plots of land with many owners, as the families continue to grow and split the available areas within family members. Lack of planning and the competition of traditional products with imported volumes at lower price result in lower benefits for the small producers.

Guatemala has a high potential for agriculture, with over 3.7 million hectares of land considered arable. Basic grains, like maize and beans, are cultivated in more than 1 million ha. However, most of crops depend on rain regimes. At the same time, African oil palm (*Elaeis guineensis*), is cultivated in areas with less rain deficit. (FAO-Guatemala & MAGA 2012). This situation marks the "high vulnerability" to food safety, in a country where poverty extends and the production depends on the climate conditions and the rain regimes.
On the other hand, the small and medium producers are not able to exploit the whole potential of their lands due to lack of access to technical assistance, credits, markets and others. About 50,000 ha are registered to produce under artisan irrigation

Family farming produces 70% of the food reaching tables, employs 38% of the economically active population (1.9 million people), leaving 1.3 million people depending on farming. New programs (FAO-Guatemala & MAGA 2012), promoted by the Agriculture Ministry (MAGA), have been launched to support the domestic farming. However, it has been stated that so far they have failed to break the paradigm that sees peasants as objects of public charity (Caballeros 2014).

1.2 THE POTENTIAL IN REUSE OF WASTEWATER

Recovery of resources from waste is a common practice in industry, where reduction of costs is fundamental for optimizing the benefits of a company. The concept of decentralized sanitation and reuse of domestic waste applies the same idea, where the domestic byproducts are seen rather as potential sources of nutrients, water and energy (Otterpohl 2000).

The ecological sanitation (ECOSAN) approach proposes the local recovery of water resources and the production of fertilizers from human waste while simultaneously reducing the health risks associated with lack of sanitation. This concept has a special potential significance in rural communities of developing countries, where, besides the underdevelopment of sanitation facilities, agricultural production is commonly the source of income (Morel & Diener 2006). It is speculated that, under appropriate treatment, domestic greywater can be a potential extra source of water for domestic gardens and small-scale irrigation. This is furthermore beneficial in areas where drought is a risk and improved sanitation could add income to the families.

The Onsite Wastewater Differentiable Treatment System (OWDTS) is an ecological sanitation alternative based on the "don't mix" and "don't collect" principles that proposes source separation and treatment of excreta, reduced volume urine, higher load greywater (HLGW) and lower load greywater (LLGW) (López-Zavala *et al.* 2002). Reclamation of domestic greywater is of particular interest since it generally contains lower concentration of organic matters and pathogens compared to mixed wastewater (Eriksson *et al.* 2002; Gajurel *et al.* 2003; Friedler & Hadari 2006). Typically, HLGW includes greywater from kitchen sink, laundry (totally or partially) and dishwasher, while LLGW is formed by effluents from shower, bath and hand basin.

Treatment of excreta through dry bio-toilet was proposed for production of compost to be used as fertilizer. Urine can be transformed to slow-release fertilizer as urea-formaldehyde.

The separation of greywater into two types is based on the assumption that greywater from different sources vary in volume and concentration of pollutants (Almeida *et al.* 1999; Funamizu *et al.* 2002; Friedler 2004), thus reducing the treatment required for certain effluents. However, it is the inclusion/exclusion of kitchen sink effluent the factor that has been found to have a direct effect in the potential risk from pathogens contents in greywater (Maimon *et al.* 2014).

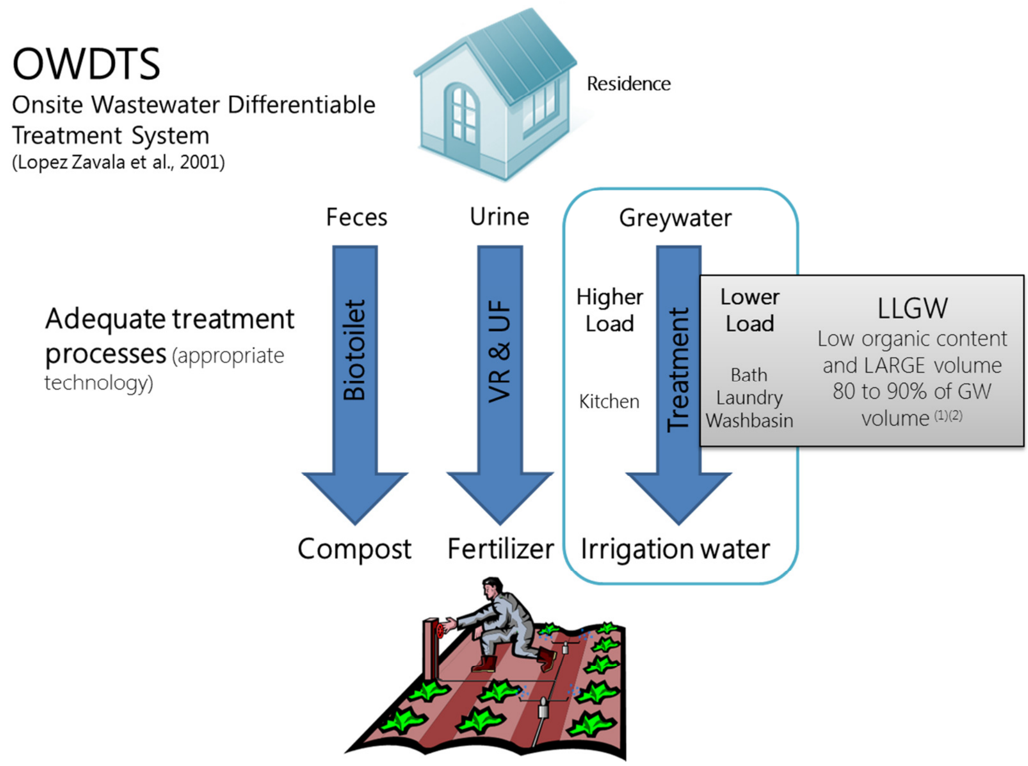


Figure 1.2 OWDTS Scheme

Despite the potential in reuse of greywater, there are several concerns regarding safety issues, in particular with the risks of direct or indirect exposure to pathogens or toxic chemicals in the raw or inadequately treated greywater.

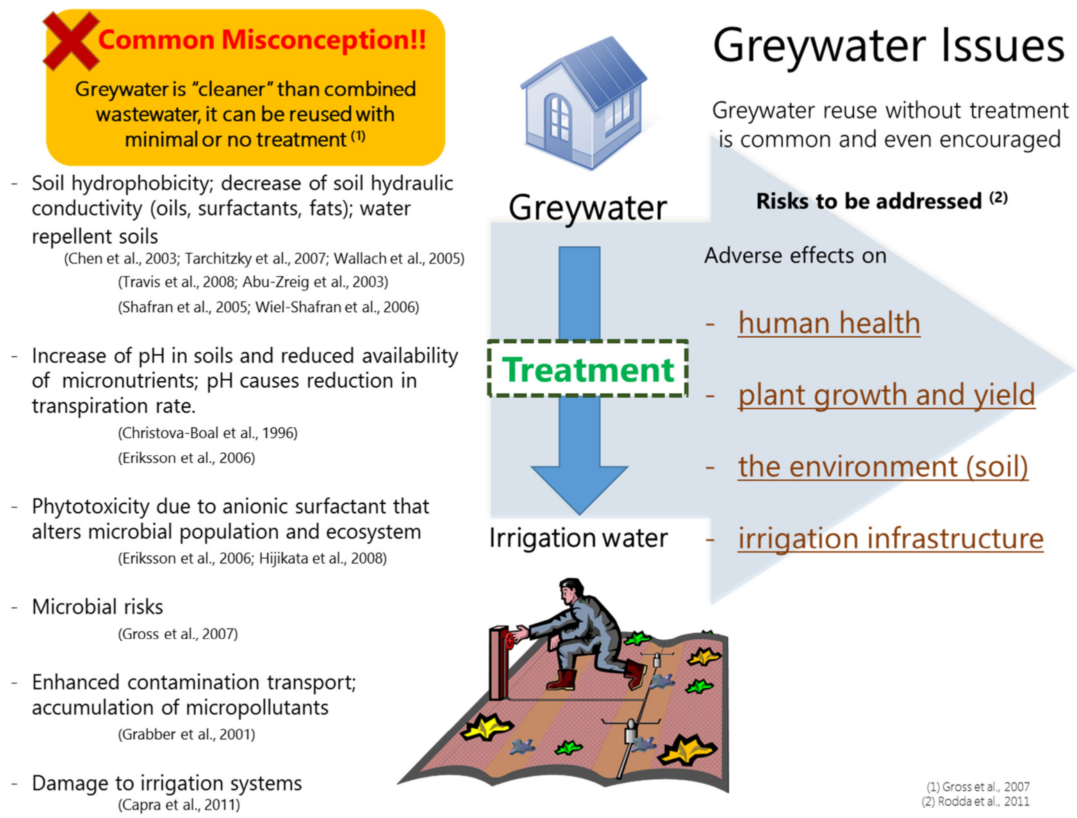


Figure 1.3 Summary of greywater reuse issues

Furthermore, for a system to be successfully implemented it has to implicate larger benefits than costs and simple low-cost, low-energy technology might be suitable.

1.3 TREATMENT TECHNOLOGIES: INTERMITTENT SAND BIOREACTORS

Several technologies have been used for treatment of domestic wastewater including constructed wetlands (Dallas *et al.* 2004; Gross *et al.* 2007). The treatment of HLGW by membrane bioreactors for urban non-potable reuse (Huelgas & Funamizu 2010) and by slanted soil system for reuse in irrigation (Ushijima *et al.* 2013) has been explored. However, when considering the scale of a single housing unit, systems that are too complex and require periodical qualified labor for maintenance and/or energy inputs may still be a barrier for implementation in low income areas.

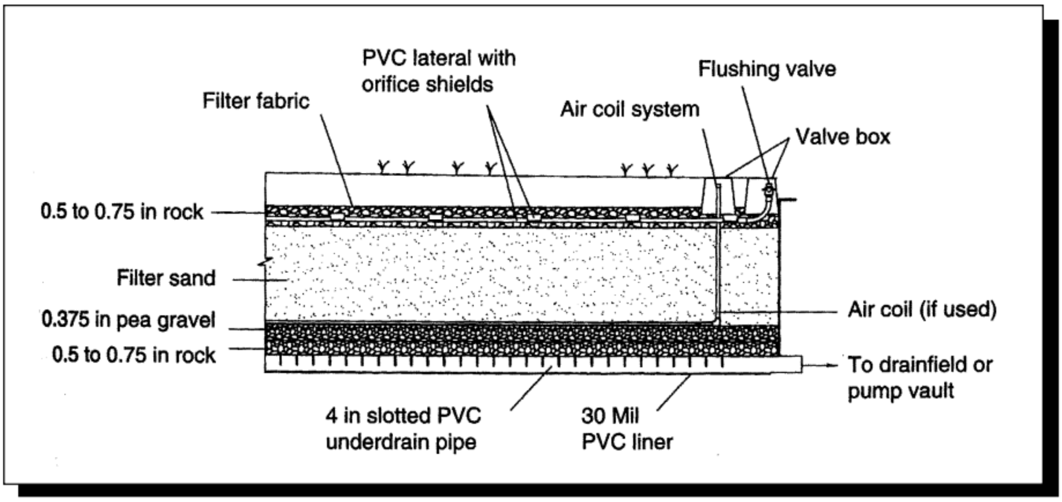


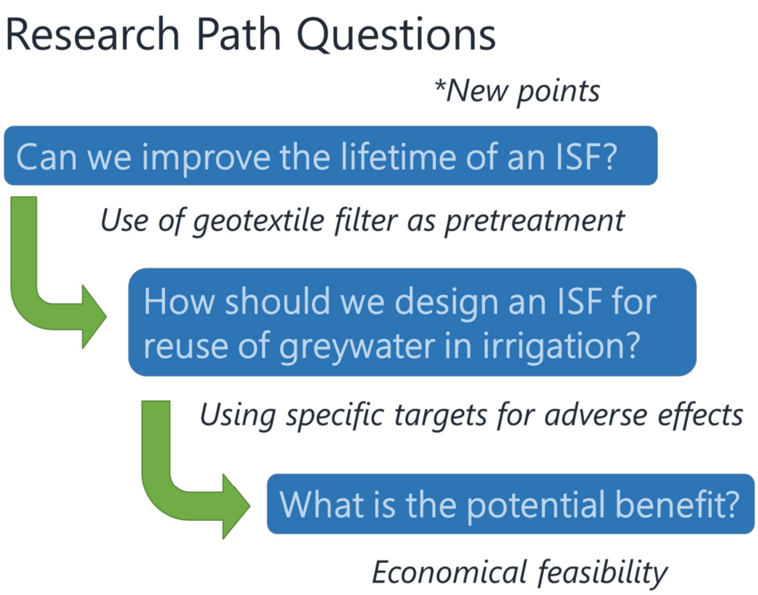
Figure 1.4 Typical cross section of an intermittent sand filter (*Source: Orenco Systems, 1998)*

On the other hand, intermittent sand filtration is one of the simplest and most efficient methods to treat wastewater; an intermittent sand filter (ISF) is a single-pass aerobic fixed-film bioreactor that combines physical and biological processes enhanced by the oxygen exchange due to intermittent load of influent (Reed *et al.* 1995), something typical in greywater discharge from domestic sources. Analogous systems have shown little or negligible difference compared to more complex systems under similar conditions, and furthermore, a better performance under shock conditions that are likely to occur in domestic discharges (Fountoulakis *et al.* 2009; Katukiza *et al.* 2014). A weak point of this system is the clogging and early failure by overload of SS (Spychala & Blazejewski 2003; Winter & Goetz 2003; Rodgers *et al.* 2004).

Generally, ISFs are used as a secondary treatment and their lifetime and performance depend on several factors: hydraulic loading rate (HLR), size and uniformity of media, frequency and volume of doses, the efficiency of the primary treatment, etc. (Darby *et al.* 1996; Winter & Goetz 2003; Rodgers *et al.* 2010). Generally, HLR, inversely proportional to the surface area of the bioreactor, will determine its lifetime. Furthermore, although the ISF systems are resilient to variations in the flow, it is likely that the quality of the effluent will decrease when increasing the loads. Therefore, it is needed to evaluate the performance of ISFs under different HLRs to assess its efficiency and limitations in reclamation of greywater for irrigation.

1.4 RESEARCH OBJECTIVES

The primary objective of this study is to evaluate the potential improvement of a simple intermittent sand filter bioreactor to be implemented in rural area households and treat the domestic greywater effluents for reuse in irrigation. Three aspects are to be investigated:



Split into the following five specific objectives:

1) To improve the lifetime of a sand filter bioreactor by implementing a more efficient pretreatment

2) Evaluate the performance of ISF bioreactors with different physical configurations in terms of:

    - Depth

    - Media size (stratified or single layers)

3) Evaluate the performance of ISF bioreactors with different hydraulic loading rates

4) Evaluate the ability of ISF bioreactors to remove trace-level hydrophobic micro pollutants with potential to bio-accumulate

5) Evaluate the economic feasibility of implementing these systems in the field

1.5 BIBLIOGRAPHIC REVIEW

1.5.1 Clogging in ISFs

The reasons for the porosity reduction that causes clogging have been widely discussed, including simple accumulation of solids or fibers (Langergraber *et al.* 2003; Spychala & Blazejewski 2003; Zhao *et al.* 2009), biofilm growth (Rodgers *et al.* 2004), bacterial production of slimes(Spychala & Blazejewski 2003), precipitation of chemicals (for example, $CaCO_3$), mechanical compaction of media (Rolland *et al.* 2009) and others. Nevertheless, clogging is not caused by only one reason, but rather due to a complex combination of all these processes (Leverenz *et al.* 2009; Hua *et al.* 2010). Compared to the accumulation of solids, biofilm growth is an inherent process to bioreactors since they rely on biological degradation and is therefore controllable to certain extent by avoiding overloading and allowing enough resting time between loads (Darby *et al.* 1996). High loads and the particle size distribution of SS have been suggested to influence the clogging rate of ISFs (Winter & Goetz 2003); these loads can be significantly affected by lack of or inefficient primary treatment, which has been stressed as the main reason of failure in practical use of ISFs and other similar systems (Morel & Diener 2006).

We propose the use geotextile fabric filters as pretreatment for domestic greywater prior to treatment by simple ISF systems as a measure of protection to overload of SS. Geotextile fabrics and similar materials have been used as primary treatment for removal of SS and lint from domestic greywater (Christova Boal *et al.* 1996), municipal wastewater (Kotha 2001), combined runoff and sewage (Marino 2006), surface waters (Mulligan *et al.* 2009) and rainwater (Silva Vieira *et al.* 2013); as media for a recirculating bioreactor for treatment of domestic wastewater (Roy *et al.* 1998); and as biofilm attachment filters for municipal wastewater treatment (Korkut 2003). These materials, particularly non-woven needle-punched geotextiles, have been shown to be efficient in trapping SS and other large materials (Marino *et al.* 2006), given their complex fiber structure compared to simple strainers. Additionally, they may have some capacity in removal of pathogens (Keraita *et al.* 2008), especially helminthes. The main mechanisms for capture of particles by geotextiles are sieving and cake filtration (Korkut 2003); consequently, capture of particles will be more influenced by their size rather than density or the flow rate of the influent; this could be an advantage if compared to traditional grease traps, given the typical unsteady flow of domestic greywater sources. However, geotextiles and ISFs could be especially sensitive to oils and fats, therefore, kitchen sink greywater is excluded from treatment in this study; thus the target influent of this study is a mixture of LLGW plus laundry greywater and is referred in this paper only as greywater.

1.5.2 Reuse of greywater in agriculture

The quality of the effluent conditions whether and/or how it can be used safely without provoking imbalances in the ecology of the point of reuse. Generally, a suitable non-potable reuse for greywater is agricultural irrigation. However, reuse of raw or improperly treated greywater in irrigation can cause several problems: microbial risks (Ottoson & Stenstrom 2003; Gross *et al.* 2005), hydrophobicity in soil (Wiel-Shafran *et al.* 2006), pH changes (Christova Boal *et al.* 1996; Eriksson *et al.* 2006), phytotoxicity (Hijikata *et al.* 2011), damage to irrigation systems (Capra & Scicolone 2007), and potential accumulation of organic micro pollutants (Ternes & Joss 2006). On the other hand, removal of nutrients (N and P), which is a major concern for environmental discharge of effluents, can be overlooked in this scenario since those contents can be of benefit for crops.

In short, three risks should be addressed when treating greywater for irrigation reuse: adverse effects to human health, damage to irrigation infrastructure and effects on plants and soil.

1.5.2.1 Human health

The World Health Organization Guidelines for Wastewater Use in Agriculture (WHO 2006) sets 2 to7 $\log_{10}$ reduction of pathogens as suitable quality for human contact, depending on the type of crop, irrigation system and handling intensity of the effluent.

These targets were set by assuming a reported 7 log CFU mL^{-1} concentration of indicator pathogen in raw wastewater; however, domestic greywater has been reported to have a lower concentration of between $10^{1.2}$ to $10^{5.4}$ CFU mL^{-1} (Ottoson & Stenstrom 2003); assuming a value of 5 log CFU mL^{-1} (higher-end of the observed range) the target of reduction for this study is 0 to 5 log.

1.5.2.2 Irrigation

The need to increase water productivity through several means, including improving the irrigation schemes has been reported (FAO 2012). Thus, subsurface drip irrigation, a high-efficiency delivery system suited for sites with low water availability that demands high quality of water, has been considered as nominal target.

Subsurface drip irrigation is a low-pressure, high efficiency irrigation system that uses buried drip tubes or tape to meet crop water needs. This system is especially suitable for arid, semi-arid, hot and windy areas with limited water supply (Reich *et al.* 2014).

Capra & Scicolone (2007) evaluated the performance of several drip irrigation systems and the occurrence of clogging when different types of wastewater were used as influent. They suggested that treated wastewater with SS below 3 mg L^{-1} showed similar performance compared to conventional irrigation water in terms of maintenance frequency requirements; therefore, this target was chosen as reference.

1.5.2.3 Surfactants

Surfactants are typical chemicals in greywater with potential to cause environmental damage to soils and crops (Scott & Jones 2000; Ying 2006). Anionic surfactants have been found to change the hydraulic characteristics of soil when discharged at high concentrations and for extended periods of time (Abu-Zreig *et al.* 2003; Wiel-Shafran *et al.* 2006; Travis *et al.* 2010), potentially altering the flow patterns and productivity.

Among all the different types of surfactants used around the World, the anionic linear alkylbenzene sulfonates (LAS) has been reported as the most consumed type, about 30% of the total (Ying 2006; Mungray & Kumar 2009). Regarding the potential phytotoxicity effects from LAS at high concentrations in greywater, Hijikata *et al.* (2011) has suggested the value to be below 8 mg L^{-1}. This value has been chosen as minimum required target.

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Chapter 2

TREATMENT OF GREYWATER BY GEOTEXTILE FILTER AND INTERMITTENT SAND FILTRATION

2.1 INTRODUCTION

The aim of this chapter is to evaluate the ability of different geotextiles to remove SS from greywater and extend the lifetime of simple ISFs by controlling the accumulation of particles. Two features are discussed: first, the lifetime and efficiency of geotextile to remove SS and chemical oxygen demand (COD) from greywater and second, the effects of using this pretreatment on the permeability and accumulated materials in the surface of ISFs fed with greywater.

2.2 MATERIALS AND METHODS

2.2.1 Evaluation of geotextiles

Six geotextile materials (provided by Toyobo Co. and Mexichem S.A.B. de C.V.) were selected to evaluate their capability as single-layer direct filters to remove SS and COD from greywater (Table 2.1). All the materials were polypropylene nonwoven needle-punched geotextiles with apparent opening size (AOS) ranging from 0.10 to 0.18 mm and thickness from 1.4 to 2.3 mm. Samples of each material were cut from a roll (2×20m or 1×20m) of geotextile provided as is in general distribution.

Table 2.1 Characteristics of Geotextile Fabrics

Type	Manufacturer	Model	AOS [mm]	Permeability [cm s^{-1}]	Thickness [mm]	Weight [g m^{-2}]
NP	Toyobo	4061N	0.14	0.150	1.00	83
NP	Toyobo	4101N	0.12	0.200	1.40	106
NP	Toyobo	4161N	0.10	0.250	2.00	171
TBNP	Mexichem	NT 1800	0.18	0.040	1.70	144
TBNP	Mexichem	NT 2000	0.18	0.042	1.90	174
TBNP	Mexichem	NT 3000	0.15	0.042	2.10	235

AOS: Apparent opening size (pore)
NP: Needlepunched
TBNP: Thermalbonded needlepunched

To evaluate the reduction in permeability of the geotextile, a device designed according to ASTM D4491–99a (American Society for Testing and Materials 2004) requirements was constructed with PVC pipes and accessories. The procedure was as follows: a sample of geotextile was cut in circular shape and installed in the device sample holder. The effective diameter was 5 cm. Then, permittivity was measured three consecutive times using water and the arithmetic average was calculated. After that, a batch of 50 cm of greywater was loaded to the geotextile sample and the filtrate collected. Permittivity was measured again with water. The process of loading batches and measuring permittivity was repeated until permittivity was under ten percent of original and it was considered as clogged.

The quality assessment of influent greywater and collected filtrates was done in terms of SS and COD. The material with the best performance, i.e. higher removal of SS and COD, was subsequently examined for a more detailed analysis regarding the particle size distribution of SS in the effluent. Fractions of SS by size were determined by filtering enough volume (5-6 L) of the filtrate through US Standard steel mesh sieves number 100, 200, 400 (nominal pore size of 150, 75 and 32µm , respectively) and glass fiber filter ADVANTEC GB-140 (pore size 0.40 µm) and measuring the individual suspended solids concentration of each filtrate. The load and sampling of greywater was done in similar method as the preliminary experiment in batches of 50 cm.

2.2.2 Evaluation of Intermittent Sand Filters

Four ISFs were constructed with acrylic Lucite plastic tubes with 0.05 m inner diameter and 1.32 m length (Figure 2.1). Media depth was 1 m, leaving 0.16 m between the sand surface and the geotextile filter to avoid mix-up and interference between the clogging either in sand surface or in the geotextile. Two filters (each constructed with and without geotextile) contained sand with an effective size (d_{10}, i.e. size of screen opening through which 10 percent by weight of sand passes) of either 0.30 mm (fine) or 0.60 mm (medium). The sand was obtained from a company that supplies the material typically used in large sand filters of local wastewater treatment plants; it was washed, dried, sieved (mesh nominal opening sizes: 0.125, 0.3, 0.425, 0.60, 0.85, 1.20, 2.0 mm) and then graded. The uniformity coefficients (UC), calculated as d_{60}/d_{10}, were 1.4 and 1.66 for fine and medium sand, respectively. The inclusion of only fine and medium size media was also intended to observe more clearly the effects of deposited solids, since the porosity is supposed to be smaller than in coarser media and therefore more susceptible to clogging.

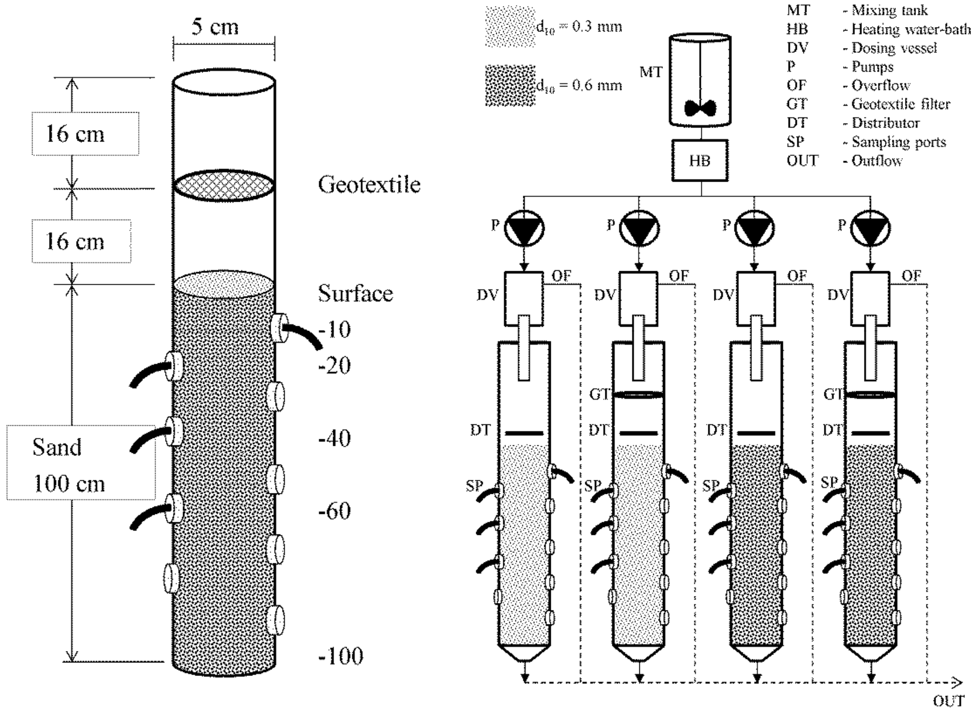


Fig. 2.1 Individual ISF and experimental setup

Sampling ports of 2.5 cm diameter were installed at depths 0.1, 0.2, 0.4 and 0.6 m from the media surface to determine the COD and LAS removal efficiency in the ISFs. These ports were used only in the last two weeks to avoid any disturbance to the ISFs and when the microbial populations had likely already stabilized. The ISFs were operated for 60 days. The conditions were set such as to be able to observe clear differences due to overloading of SS. For the first six weeks, effluent was collected only at the bottom of each ISF. Since the greywater volume of each discharge was small, only one port was opened in each sampling, starting from depth 0.6 and going upwards; this took a week for evaluation at all depths.

The geotextile filter for pretreatment was installed in two of the ISFs through a stainless steel ring equipped with rubber seals to ensure the flow of greywater would go only through the material; the inner diameter of the steel ring was 0.05 m. The geotextile filter was replaced every time it became clogged (i.e. incomplete infiltration after 24 h), which occurred every 7 to 10 days.

A greywater hydraulic loading rate (HLR) of 16 cm d^{-1} was applied based on the recommendation of Darby *et al.* (1996). SS and COD loading rates were 16 g m^{-2} d^{-1} and 57 g m^{-2} d^{-1}, respectively. The total daily volume was split into three equal single-time discharges during daytime (9 AM , 12 PM and 6 PM), corresponding to a theoretical morning, noon and evening time peak water use (Funamizu *et al.* 2002).

Effects of geotextile filter on ISF performance were measured by two factors: permeability of surface (in terms of infiltration time of a single given greywater dose) and effluent quality. To use a conventional permeability test was deemed impractical since this could cause disturbances to the normal accumulation of SS and the natural development of ISFs biofilm under greywater loading. Therefore, the permeability of media was measured by the total time in seconds that it took for a single morning discharge of 5.66 cm to completely infiltrate (i.e. no water line observed above sand) the surface. Additionally, post experiment weight loss on ignition (LOI) of sand layers at different depths (3 samples were taken from each depth: 0.025, 0.075, 0.15, 0.25, 0.35, 0.5, 0.7 and 0.9 m, respectively) were performed to determine the difference in organic material accumulated as an indicator of physical clogging (Rodgers *et al.* 2004). Samples for LOI were first evaluated for moisture content and subsequently burned in a muffle furnace at 550°C for two hours. Difference between initial dry weight and burnt weight in percentage was calculated as LOI.

2.2.3 Greywater characteristics

Composition of greywater was a mixture of shower, laundry and hand basin sources (65:30:5 in volume) with the characteristics summarized in Table 2. Shower and washbasin greywater was collected from a domestic household to include the organic waste originated from human body. Constituents included common brand shampoo (5g $30L^{-1}$), conditioner (5g $30L^{-1}$), body soap (5g $30L^{-1}$), toothpaste (3g $30L^{-1}$) and hand soap (3g $30L^{-1}$). Prior to preparation of greywater, each constituent was weighed in separate plastic containers with precision of 0.01 g. Then shower was taken by one person using the contents of the plastic containers. The shower drain was connected to semitransparent container tanks previously marked to the desired volume (20 L each), so the volume of accumulated greywater was visible and was collected with relative accuracy.

Laundry greywater was prepared by washing four pieces of used clothes in a washing machine using 12.5 g of detergent (Unilever OMO) per 40 L of water; this detergent was chosen since linear alkyl benzene sulfonates (LAS) are the active surfactant. LAS have been estimated to be the most widely used synthetic anionic surfactants and may have a negative impact on environment (Mungray & Kumar 2009) . LAS can exist in high concentrations in greywater and thus it is a useful indicator compound for greywater treatment systems that aim for reuse of effluent.

After preparation, both types of greywater were transported, mixed in the volume ratio indicated and stored in refrigerator at 3-4°C under constant stirring to maintain a homogeneous particle suspension. Fresh greywater was prepared every five days. Typical temperature of greywater is in the range of 18 to 38°C (Eriksson *et al.* 2002); therefore, the influent was passed through a water bath that heated it to a temperature of 20°C before being supplied to the ISFs. In general, the quality of the experimental greywater (SS and COD) was in the low to middle range for raw greywater (Almeida *et al.* 1999; Morel & Diener 2006), but higher than usual influents from septic tanks or pond effluents loaded to ISFs (Darby *et al.* 1996).

Table 2.2 Influent Characteristics

	Average	Min	Max
TCOD [mg L^{-1}]	357	210	505
DCOD [mg L^{-1}]	187	65	335
SS [mg L^{-1}]	100	75	124
DS [mg L^{-1}]	240	196	272
TN [mg L^{-1}]	7.5	4.1	13.7
TP[mg L^{-1}]	7.5	5.2	10.0
LAS [mg L^{-1}]	25	-	-

2.2.4 Sample analysis

Permittivity of geotextiles was evaluated using the ASTM D4491–99a Falling Head Method; normalized values were used for a better comparison. Influent and effluent samples were analyzed for suspended and dissolved solids (SS and DS), total and dissolved COD (TCOD and DCOD), total phosphorus (TP), total nitrogen (TN) and linear alkyl benzene sulfonates (LAS). Standard analytical methods were used for SS and DS (American Public Health Association *et al.* 1989) . HACH kits were used for COD, TN and TP (Method 8000, Method 10071 and Method 8190, respectively) with the HACH DR2800 Spectrophotometer.

Concentration of LAS (C10 to C14) was determined using liquid chromatography mass spectrometry (LC-MS) based on Ushijima *et al.* (2013). Column used was Wakopak ® WS-Aqua (4.5x250mm) and mobile phase were 0.2 mMol ammonium acetate and 100% acetonitrile, ratio 63:37 at 0.3 mL min^{-1} in isocratic mode. Samples for solid phase extraction were spiked with recovery standard C8 surrogate and then diluted to a concentration in the range of the limit of detection (0.01 to 0.25 mg L^{-1}). Solid phase extraction was performed according to Managaki *et al.* (2005) as follows: the pH was adjusted to 3±0.05 with 10% HCl solution and loaded to a BOND ELUTE® PPL cartridge previously conditioned with 10 mL of methanol and 10 mL of pure water adjusted to pH 3±0.05. LAS were eluted from the cartridge with 10 ml of methanol and subsequently filtered with a 0.2 μm PTFE Dismic filter and aliquots were loaded to the LC-MS vials. Standard LAS solution (C10 to 14) and recovery standard C8 reagent were obtained from WAKO Industries (>99% purity). Recovery rates were 92, 90, 87, 75 and 64%, respectively.

2.3 RESULTS

2.2.5 Performance of geotextiles

As shown on the range in Table 2.2, the SS and COD concentration in greywater fluctuated significantly each time despite following the same recipe for greywater in each preparation; this is probably due to the alternate type of clothes used for laundry greywater as well as the variability of the load of human waste that depend on personal habits and activities.

The permeability of geotextiles, indirectly estimated in terms of permittivity, followed a steep reduction over the course of loading greywater (Figure 2.2). From the six models evaluated, only model 4061N showed a slower reduction of permeability, just 20.99% loss after 300 mL cm^{-2} of greywater were loaded. At the same point, all the other models were already below 10% of original permittivity. The materials captured by geotextile included hair, cloth fibers and small clumps of particles or biofilm.

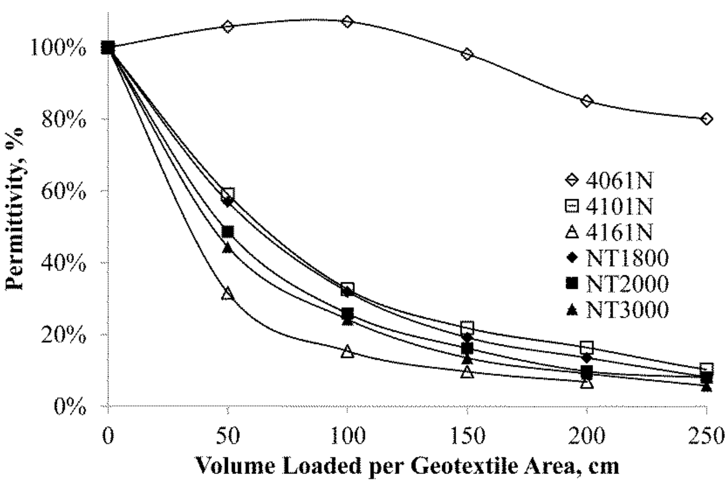


Fig. 2.2 Permittivity reduction in geotextiles

Differences in removal rate of SS were negligible in the initial conditions, but generally, after loading 100 cm it was possible to observe difference in the behavior of the materials (Figure 2.3). Overall, only the geotextile models with density above 170 g m^{-2} (4161N, NT2000 and NT3000) achieved removal rates above 50% of the SS. Table 2.3 shows the average SS and TCOD removal by geotextiles, where the maximum value of the range refers to the last measured removal before permittivity value was below 10% of original.

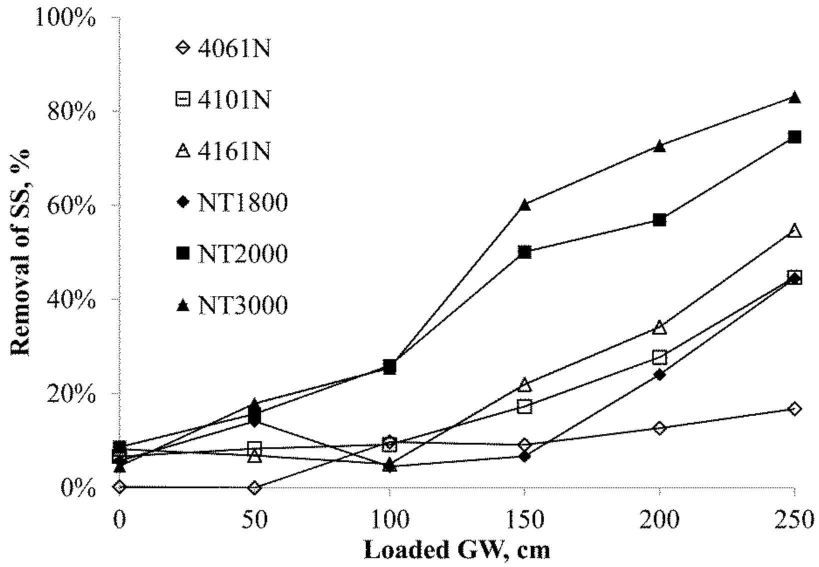


Fig. 2.3 SS removal by geotextiles

Table 2.3 SS and COD Removal by Geotextiles

	SS		COD	
Geotextile	Removal [%]	Range [%]	Removal [%]	Range [%]
4061N	8.1	0.0 - 16.8	3.0	0.0 - 5.4
4101N	19	6.7 - 44.7	10.3	2.0 - 20.5
4161N	21.8	5.0 - 54.7	11.3	2.9 - 26.0
NT1800	16.6	4.5 - 44.5	6.7	1.0 - 15.4
NT2000	38.6	8.6 - 74.5	20.3	5.2 - 32.0
NT3000	44	4.6 - 83.1	19.6	7.5 - 34.2

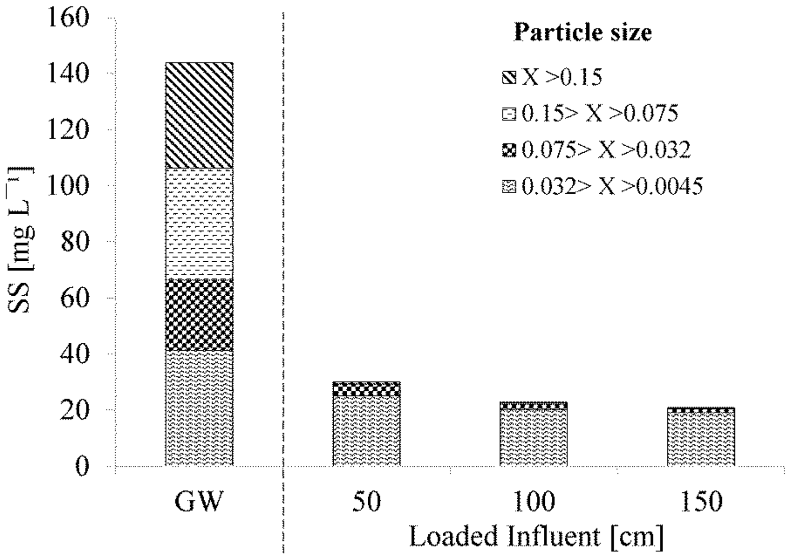


Fig. 2.4 Particle size distribution in GW filtered by NT3000

For the filter experiment, geotextile NT3000 was chosen due to its ability to capture more SS compared to other models. Since the quality of greywater is variable, several samples of NT3000 were individually assessed about the specific size of the particles removed; this is of importance since the size of deposited particles has been cited as one possible factor in ISF clogging. Figure 4 shows fractioned removal of SS by geotextile NT3000 for one sample batch test when greywater had a SS concentration of 143 mg L^{-1}, from which 77 mg L^{-1} were solids larger than 0.075 mm. SS removal had a high initial value and sustained increase in quality, from 79 to 85%, the remaining SS in filtrate being mostly solids smaller than 0.032mm. Although the pore size of NT3000 is 0.15 mm, the material was able to remove SS in smaller fractions. Permeability was significantly reduced after only 150 cm.

2.2.6 Performance of ISFs and geotextile filter

The performance of the geotextile was slightly different compared to the first experiment. In this longer-term operation, insects and other random materials were occasionally observed, additionally to the previously mentioned greywater contents. The geotextile filter had to be replaced every 7 to 10 days, which means it only filtered 112 to 160 cm, compared to the 250 to 300 cm observed in the preliminary tests. Some type of slime was observed on the surface of the geotextile but not measured in any way; this could, however, indicate some bacterial activity.

Figure 2.5 shows the progression in infiltration time for a single dose (5.66 cm) on the surface layer of the ISFs, as an indirect measurement of its hydraulic permeability. A clear increase in infiltration time was observed for three of the cases (0.30mm with and without geotextile and the 0.60 mm without geotextile). Differences started to be noticeable after just two weeks. ISF without geotextile and fine sand was clogged after 29 days, after an almost exponential increase in the infiltration time in its last week. On day 28th the total daily dose of 16 cm did not completely infiltrate from the previous day; the column was stopped at the end of day 29th, letting it to rest for one more day and then proceeded to disassembling. Loss on ignition test was performed immediately. The ISF with same media but geotextile did experience sustained increase in infiltration time, although on a slower rate.

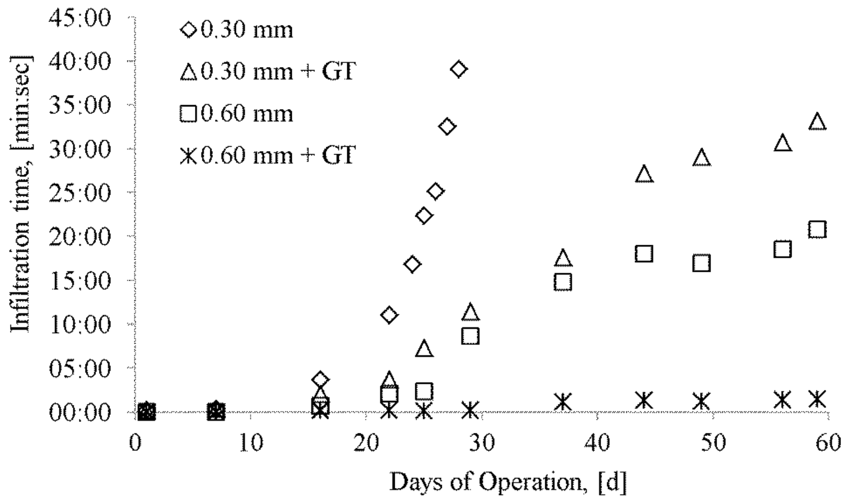


Fig. 2.5 Infiltration time of a single dose of GW in ISFs

For the case of 0.60 mm sand with geotextile pretreatment the decrease in permeability was the least severe, increasing from 17 seconds in the initial day to 92 seconds in day 60. Although there was an increment in the infiltration time, the increase rate was significantly slower compared to the case without geotextile.

The remaining three ISFs were dismantled after 60 days of operation and the LOI tests were performed. Figure 2.6 shows the difference in weight loss in each of the layers. The most notable difference is observed in the top layer (0 m to 0.05 m depth). ISF of media 0.60 mm with geotextile had a weigh loss of only 0.49%, whereas the one without filter was 0.77%. ISFs with media 0.30 mm with and without geotextile had 0.89% and 0.92% weigh loss. The LOI values from below surface were similar for all ISFs.

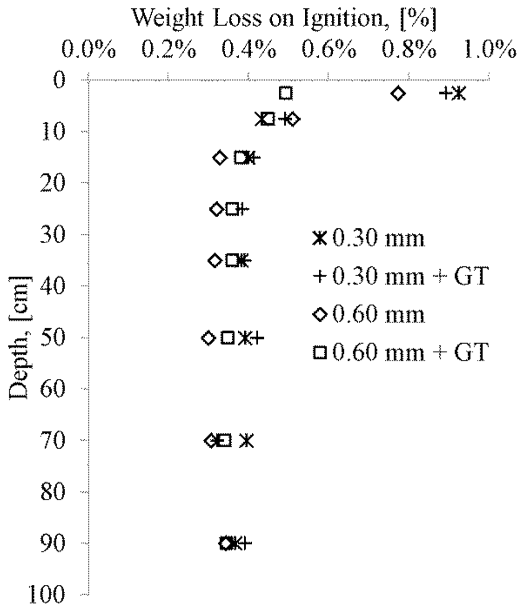


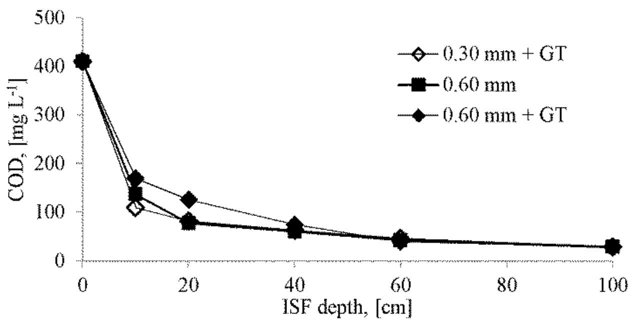
Fig. 2.6 Accumulation of organic material in ISFs

Furthermore, following experiments showed that after operating for more than 8 months in similar conditions, no clogging was observed in media size d_{10}=0.60 mm (data not shown). This confirms the ability of geotextile to extend lifetime of ISFs over a continuous usage. At depth 100 cm the quality of effluent from ISFs was high in terms of both SS (less than 1 mg L^{-1} in all cases) and organic matter (COD removal over 90%). The quality of the effluents did not significantly vary between the columns of same media size (Table 2.4).

Table 2.4 Effluent quality

Parameter	GW	0.30mm	0.30mm +GT	0.60mm	0.60mm +GT
COD [mg L^{-1}]	357.4±72.0	30.5±18.9	27.5±16.2	32.6±14.2	33.7±18.9
SS [mg L^{-1}]	99.9±14.7	< 1	< 1	< 1	< 1
TN [mg L^{-1}]	7.5±2.9	1.9±1.4	2.9±2.4	3.5±1.5	3.0±1.9
TP [mg L^{-1}]	7.5±1.5	1.2±0.2	1.2±0.3	1.1±0.2	0.9±0.1
LAS [mg L^{-1}]	25	3.0±1.2	3.0±1.5	3.5±1.0	3.9±1.2

The profile obtained in the last two weeks for the three remaining columns through samplings in the ports provided information about the degradation of organic components (Figure 2.7 and 2.8). COD reduction was drastic in the upper 10 cm, whereas LAS removal had a more linear relationship to depth, reaching overall efficiencies of 88% and 84-86% for fine and medium sand, respectively.



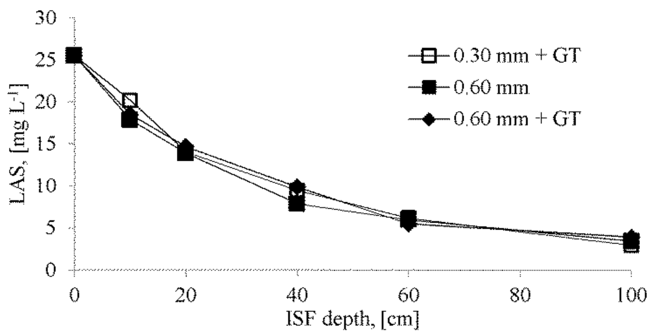


Fig. 2.7 COD reaction in ISFs

Fig. 2.8 LAS reaction in ISFs

2.4 DISCUSSION

As shown in the results from the first phase, the geotextiles have a remarkable ability to remove SS and COD in particulate form. Moreover, the particle size can be controlled. In the case of a traditional sedimentation tank, the removal of SS depends on the retention time, something difficult to control in the case of sudden and intermittent discharges. Additionally, the lack of maintenance in such systems can cause a sharp increase in SS exiting the chamber, a common occurrence. Geotextile filtration appears to be a good option to control the size of particles, although the maintenance required for current method of use seems a downside. In a previous study by Marino (2006) a geotextile was evaluated in removal of organic particles under horizontal flow, the material was able to separate the large elements and when the flow stopped, the retained material subsequently slurred, giving an idea of geotextile working as a simple mesh and separating particles of a given size; however, the nature of particles in greywater is different in the sense that particles attach to the fibers of the geotextile, giving little chance to reuse the filter under the current usage conditions.

The inclusion of geotextile in a self-cleaning backwash system set-up as shown in Silva Vieira *et al.* (2013) could enhance its lifetime and reduce the frequency of maintenance. In that scheme the geotextile was installed in an inverted siphon setup, performing an up-flow filtration rather than top to bottom as in this study. This set-up allowed the retained SS to settle in the bottom of the siphon after the influent stopped to be loaded. Furthermore, a magnetic valve located in the bottom part of the siphon opened under certain head pressure, allowing the automatic backwash when the accumulated liquid equilibrated the strength of the magnet. Although the influent in that study was rainwater, the same principle applied for greywater system could be a good option to be examined for a longer lifetime of geotextile.

Thermal bonded side of geotextile materials NT1800, 2000 and 3000 seemed to be beneficial on the initial sieving capture of SS and certainly the structure of the geotextile was more robust since the fibers were bonded together. Besides this characteristic, another important factor in removing particles seems to be the density of the materials. Despite having a theoretical smaller AOS and similar thickness, the model 4161N performance in removal of SS and COD was slightly below models NT2000 and NT3000, and above NT1800, an order which correlates to the densities shown in Table 14.1.

The improvement in performance over the course of loading greywater to geotextiles is undoubtedly due to the accumulation of trapped particles in the fibers of the filter and a logical reduction of porosity, as well as the formation of a cake layer. This is clearly shown when the SS load of larger particles was higher (Figure 4). The removal rates jumped to near 80%, although with a reduced lifetime.

The effect of geotextile on the permeability of the ISFs was evident, although the experimental conditions were somewhat near worst case scenario for the two columns without pretreatment. However, it was clear that the short term clogging was avoided by pretreatment. Geotextile reduced the SS load, thus reducing the particulate accumulation in surface, which was not only important regarding the total volume but also the type and size of particles trapped; the geotextile removed not only particles, but also fibers originated in clothes, which had previously been suggested by Spychala & Blazejewski (2003) to contribute to the acceleration of clogging in sand filters. These type of SS probably have a higher chance to breakthrough a sedimentation tank, most likely if those are low density synthetic fabrics, something that adds the complication of no biodegradation. Geotextile has a remarkable ability to trap such materials and similar (hair) within its complex array of fibers, compared to a simple metallic mesh. On the long run this process could extend lifetime of a sand filter.

The quality of effluent in ISFs did not show any significant difference and, as expected, the top layer of the filters was the most important for the removal of COD and SS, mainly due to the capture of the particulate portion by sieving. The near linear pattern in LAS concentration to depth shows that removal may be initially influenced by adsorption process followed by biodegradation.

Biofilm growth is a process inherent to this type of bioreactors, but if the system works under appropriate conditions and resting times are allowed periodically the system can have a stable performance for long periods of time. Clogging by deposition of large and non-degradable materials on the other hand is an avoidable process.

2.5 CONCLUSIONS

Geotextiles showed to be able to remove more than 50% of SS in greywater. Moreover, the removal of specific particles goes below the theoretical AOS. Reduction of large particles by pretreatment not only reduces the amount of accumulated particles but showed the potential to remove COD up to 30%. The materials with one side thermal-bonded as well as higher density showed best performance. The materials were able to filter an overall maximum of 200 to 250 cm of greywater before failure in the continuous use, and only 112 to 160 cm in the intermittent setup, meaning that if used in the same area ratio to the ISFs surface, a large amount of geotextile is needed to be replaced often. Using geotextile filter as pretreatment did not affect significantly the overall quality of ISFs effluent and positively reduced the accumulated volatile solids in the top layers of the media, effectively avoiding early clogging in fine media and decrease of permeability in medium sand during the experimental period.

The results of the experiment show that geotextile filter may have potential for extending the initial lifetime of ISFs. The downside is the periodical maintenance and the material expense needed every 7 to 10 days in the current usage form. It is recommended to explore alternative usage techniques to address this matter. Promising alternatives could be the usage of layered packed geotextile and/or the up-flow layout shown in some rainwater oriented systems, but a cost-effectiveness assessment is needed for evaluating the real value of integrating such pretreatment in ISF systems.

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Chapter 3

INFLUENCE OF PHYSICAL PARAMETERS ON PERFORMANCE OF INTERMITTENT SAND FILTERS FOR TREATMENT OF GREYWATER

3.1 INTRODUCTION

The overall objective of this Chapter was to evaluate the effects of physical characteristics of a simple ISF: depth, media size and media stratification in achieving the required quality of the effluent for greywater to be reused in irrigation regarding the targets set previously under a conservative HLR.

In short, three adverse effects should be addressed when treating GW for irrigation reuse: human health, damages to irrigation infrastructure and effects on plants and soil. Regarding the first parameter, the World Health Organization Guidelines for Wastewater Use in Agriculture (WHO 2006) sets 2 to7 log_{10} reduction of pathogens as suitable quality for human contact, depending on the type of crop, irrigation system and handling intensity of the effluent. These targets were set by assuming a reported 7 log CFU mL^{-1} concentration of indicator pathogen in raw wastewater; however, domestic greywater has been reported to have a lower concentration of between $10^{1.2}$ to $10^{5.4}$ CFU mL^{-1} (Ottoson & Stenstrom 2003); assuming a value of 5 log CFU mL^{-1} (higher-end of the observed range) the target of reduction for this study is 0 to 5 log.

Concerning the effects on the performance of irrigation systems, choosing a parameter as target is difficult, since every type of system can have different specific requirements. The need to increase water productivity through several means, including improving the irrigation schemes has been reported (FAO 2012). Thus, drip irrigation, a high-efficiency delivery system suited for sites with low water availability that demands high quality of water, has been considered as nominal target. Capra & Scicolone (2007) evaluated the performance of several drip irrigation systems and the occurrence of clogging when different types of wastewater were used as influent. That study showed that treated wastewater with SS below 3 mg L^{-1} and low BOD (i.e. high quality) had similar performance compared to conventional irrigation water and didn't have a significant difference in the frequency of required maintenance; therefore, this target was chosen as reference.

Surfactants are typical chemicals in greywater with potential to cause environmental damage to soils and crops (Scott & Jones 2000; Ying 2006). Anionic surfactants have been found to change the hydraulic characteristics of soil when discharged at high concentrations and for extended periods of time (Abu-Zreig *et al.* 2003; Wiel-Shafran *et al.* 2006; Travis *et al.* 2010), potentially altering the flow patterns and productivity. One of those, linear alkyl benzene sulfonates (LAS), are the most common surfactants used in the World and have been found to cause phytotoxicity in plants if supplied at high concentration. Hijikata *et al.* (2011) has suggested the value of 8 mg L^{-1} as the maximum concentration of LAS to avoid accumulation and potential phytotoxicity to sensitive crops. Therefore, this value has been chosen as target for minimum requirements of effluent quality.

Geotextile filters were used previously as an effective pretreatment for greywater (Charchalac Ochoa *et al.* In press), removing up to 40% of SS and moreover controlling the particle size and trapping low density cloth fibers. Therefore, such simple pretreatment was incorporated in this experimental work as well. Generally, ISFs are used as a secondary treatment and their lifetime and performance depend on several factors: hydraulic loading rate (HLR), size and uniformity of media, frequency and volume of doses, the efficiency of the primary treatment, etc. (Darby *et al.* 1996; Winter & Goetz 2003; Healy *et al.* 2007).

3.2 MATERIALS AND METHODS

3.2.1 Intermittent sand filters assembly

A geotextile filter system (GT) designed to be in-line with the ISFs was used as pretreatment to remove SS and lint from raw greywater before being discharged to the sand media (Figure 1). A polypropylene nonwoven needle-punched TOYOBO CO Ltd geotextile model 4101N (apparent opening size of 0.12 mm, thickness 1.4 mm and weight 106 g m^{-2}) was chosen due to the availability in the experimental location. The assembly for the filter consisted of a short section (10 cm) of a 140 mm diameter PVC pipe coupled to a 140 x 75 mm PVC reducing coupling in diameter. A circular sample of geotextile (about 20 cm diameter) was stretched tightly between the pipe section and the coupling as shown in Figure 1a; the tight fitting of the tubing and adaptor ensured for the greywater to flow only through the fabric (Figure 1c). The geotextile fabric was replaced with new one when it became clogged (i.e. incomplete infiltration after 24 h), which occurred every 7 to 10 days. 20 cm were left between the sand and the bottom of the GT assembly to avoid mix-up or interference in the interpretation of clogging either in media or in the geotextile if ponding occurred.

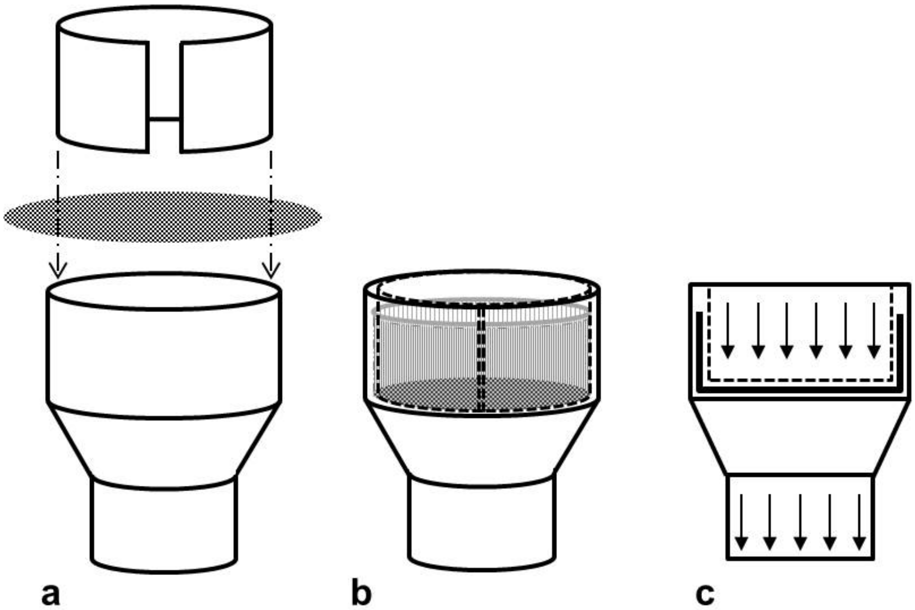

Figure 3.1 Geotextile filter assembly

Seven sand filters (A, B, C, D, E, F and G) with varying depths were constructed with transparent PVC tubing and accessories (Figure 2). Transparent PVC was used to allow observation of the accumulation of solids and growth of biomass inside the filter. Each filter had an inner nominal diameter of 13.1 cm. The bottom drainage consisted of a 5 mm-thick flat plastic punched sheet covered with a stainless steel mesh sheet with 0.2 mm sized openings. Sand filters A to F were operated together, while G was operated during another experimental run, but partial data is included here for the purpose of comparison. The ISFs were inside a chamber which was covered with black plastic to avoid penetration of sunlight.

Three media depths (H) were evaluated: 20 cm (A), 40 cm (B, C, D, G) and 60 cm (E, F). Three media sizes were prepared: d_{10}=0.30 mm (fine), d_{10}=0.60 mm (medium) and d_{10}=0.90 mm (coarse). A, B and F columns were used to evaluate the effect of depth with a uniform layer of medium sized sand; the effect of media size and layers was evaluated with B, C, D and G for 40 cm depth, and with E and F for 60 cm depth. The sand was obtained from a company that supplies material typically used in conventional sand filters of local wastewater treatment plants; it was washed, sieved and graded to obtain a uniformity coefficient (UC) of UC_{30}=1.57, UC_{60}=1.55 and UC_{90}=1.57, respectively (Figure 3). ISFs were operated for 250 days between June 2012 and March 2013 (except G, 249 days between October 2013 and May 2014).

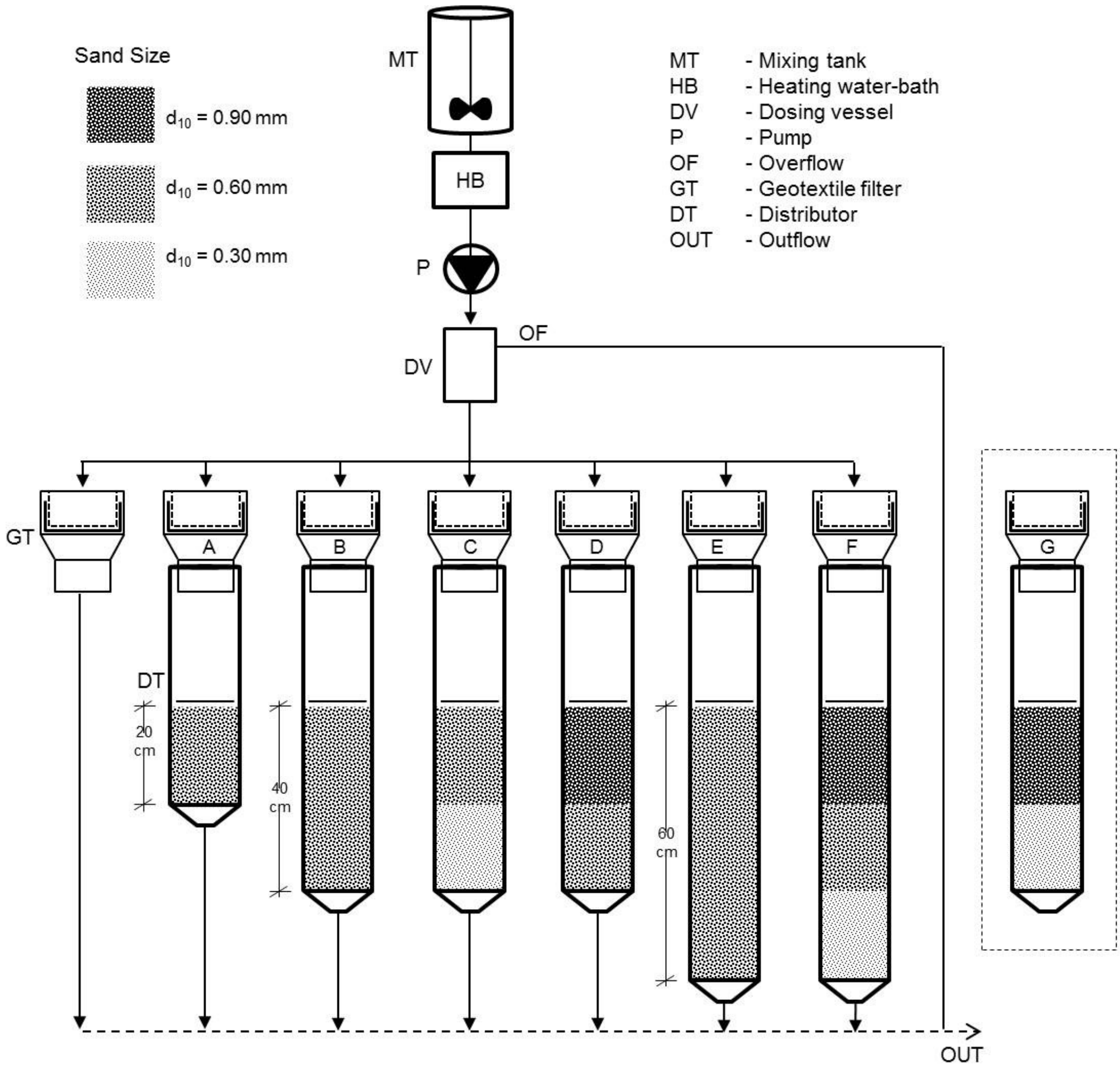

Figure 3.2 Experimental setup

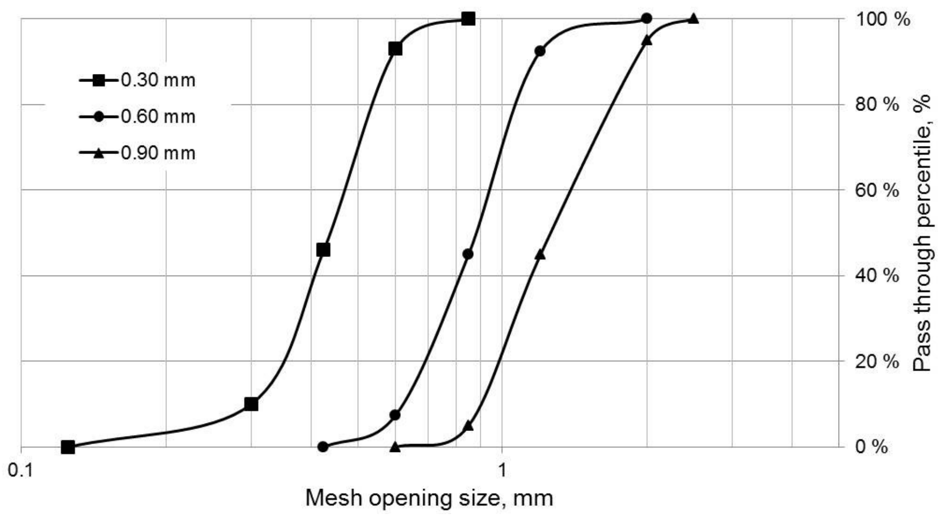

Figure 3.3 Granulometry of media

3.2.2 Greywater characteristics and loading

The greywater used in this study was a mixture of shower-handbasin and laundry effluents (60:40 in volume), excluding kitchen sink greywater as suggested by Maimon *et al.* (2014). Greywater from shower and washbasin was collected from a shower room located in the laboratory premises; this was planned to include the organic waste originated from human body. Constituents included shampoo (Unilever LUX, 5 g 30 L^{-1}), conditioner (Shiseido TSUBAKI, 5 g 30 L^{-1}), body soap (5 g 30 L^{-1}) and toothpaste (Sunstar GUM, 3 g 30 L^{-1}). Before the preparation, each constituent was weighed with a precision of 0.01 g in separate plastic containers. Then shower was taken by one person using the contents of the plastic containers. The shower drain was connected to three semitransparent water tanks marked to a 20 L level that received the effluent, so the volume of accumulated greywater was collected with relative accuracy. Laundry greywater was prepared by washing three to four pieces of clothes in a washing machine using 25 g of powder detergent (Unilever OMO) per 40 L of water; this detergent was chosen since LAS, one of the targets of this study, are the active surfactants.

Escherichia Coli NBRC 3301 strain was used as indicator of enteric bacterial pathogens. Pure stock of NBRC 3301 was first activated by 24 h incubation in triptic soy broth (TSB) in 37°C water bath agitated at 116 rpm, followed by streaking on a triptic soy agar (TSA) plate and incubated for 24h at 37°C. Subsequently a single colony was transferred with an inoculation loop to 100 mL of TSB and incubated for 4 h in a 37°C water bath at 116 rpm. The solution was poured to previously prepared 100 L of fresh greywater. By this method, the concentration in the greywater was around 1.0×10^5 CFU mL^{-1}.

After preparation, both types of greywater were transported, mixed in the volume ratio indicated and stored in a tank located inside a refrigerator at 3-4°C under constant stirring to maintain a homogeneous particle suspension. Greywater was temporarily spiked with a solution containing organic micropollutant compounds in trace levels (less than 0.1 ppm) for a separate study (data not shown). Fresh greywater was prepared every five days. Typical temperature of greywater is in the range of 18 to 38°C (Eriksson *et al.* 2002); therefore, the feeding tube from the mixing tank to the ISFs passed through a heated water bath that brought greywater to a temperature of between 17-20°C when reaching the dosing vessel. The chemical characteristics of raw greywater and effluent from geotextile (GT) are shown in Table 1. In general, the quality of the experimental greywater was in the middle range for raw greywater (Almeida *et al.* 1999; Morel & Diener 2006) for COD and SS, while low values for TN and TP.

Table 3.1
Characteristics of raw greywater and geotextile effluent

Parameter	Unit	Greywater (N=20)	GT Effluent (N=20)
SS	mg L^{-1}	110.50 ± 32.42	40.99 ± 31.48
COD	mg L^{-1}	460.13 ± 98.48	351.13 ± 112.71
Total-N	mg L^{-1}	11.91 ± 4.28	9.49 ± 3.39
NH_4^+-N	mg L^{-1}	0.77 ± 0.89	1.12 ± 0.98
NO_3^--N	mg L^{-1}	0.57 ± 0.34	0.45 ± 0.24
Total-P	mg L^{-1}	4.82 ± 1.87	3.48 ± 0.88
Ortho-P (PO_4^{3-})	mg L^{-1}	0.83 ± 0.40	0.77 ± 0.44
LAS	mg L^{-1}	43.34 ± 9.16	39.47 ± 7.97
E. Coli	CFU mL^{-1}	1.0×10^5	

Abbreviation: GT: Geotextile filter

A greywater hydraulic loading rate (HLR) of 16 cm d^{-1} was applied to the ISFs based on the recommendation of Darby *et al.* (1996). The total daily volume was split into three equal daytime 5.33 cm doses of (9 AM, 12 PM and 6 PM) corresponding to the theoretical morning, noon and evening peak time for water use (Funamizu *et al.* 2002). The greywater was pumped to a dosing vessel controlled by a valve above the GT assembly and then loaded in 5 small discharges of 7 seconds each, separated by four intervals of 53 seconds between each discharge, totaling 5 minutes for the total dose discharge. SS and COD loading rates were 17.6 g m^{-2} d^{-1} and 73.6 g m^{-2} d^{-1}, respectively.

3.2.3 Sample analysis

Influent and effluent samples were analyzed for suspended solids (SS), total and dissolved COD (TCOD and DCOD), total and dissolved phosphorus (TP and DP), orthophosphate (PO_4^{3-}-P), total and dissolved nitrogen (TN and DN), nitrate (NO_3^--N), ammonium (NH_4^+ –N), linear alkylbenzene sulfonates (LAS) and *Escherichia Coli* NBRC 3301 strain as indicator of enteric pathogens.

SS was determined by Standard Methods (American Public Health Association *et al.* 1989). COD, TN, NO^{3-}–N, NH_4^+-N, TP, PO_4^{3-}-P were measured by using HACH kits (Methods 8000, 10071, 10020, 10205, 8190 and 8048, respectively) and the HACH DR2800 Spectrophotometer. For measurement of dissolved fractions, 100 mL (greywater and geotextile effluent) and 300 mL (ISFs effluents) samples were filtered with prewashed ADVANTEC GB-140 fiber glass filters (pore size 0.4 μm) with suction filtration equipment. Particulate fractions were estimated as the difference between total and dissolved measurements for each single sampling.

Concentration of LAS (C10 to C14) was determined using liquid chromatography mass spectrometry (LC-MS) based on Managaki *et al.* (2005) and Ushijima *et al.* (2013). The samples were cleaned by solid phase extraction process (SPE) with a BOND ELUTE® PPL cartridge and LAS C8 trace recovery standard surrogate was added at 0.01 mg L^{-1} concentration. The SPE was done as follows: the cartridge was conditioned with 10 mL of methanol and 10 mL of pure water adjusted to pH 3±0.05. The pH of samples was adjusted to 3±0.05 with 10% HCl solution, surrogate added and then loaded to the conditioned cartridge. The cartridge was washed with 10 mL of water and subsequently dried under vacuum for 25 min. LAS were eluted from the cartridge with 10 ml of methanol. Aliquots were filtered with a 0.2 µm PTFE Dismic filter and loaded to the LC-MS vials. The column used for LC separation was a Wakopak ® WS-Aqua (4.5x250mm), at 40°C, and mobile phases were 0.2 mM ammonium acetate in pure water and 100% acetonitrile, ratio 63:37 under flow rate of 0.3 mL min^{-1} in isocratic mode. MS conditions are listed in Table 2. All samples were diluted to a concentration in the range of 0.01 to 0.25 mg L^{-1}, where linear relationship was observed in the chromatographic peaks. Standard LAS solution (C10 to 14) and recovery standard C8 reagent were obtained from WAKO Industries (> 99% purity).

Table 3.2

Operation conditions of LC-MS for determination of LAS

	Condition
Colum	Wakopak WS Aqua (4.5 x 50mm)
Mobile phase	A) 0.2 mM ammonium acetate in pure water B) 100% acetonitrile
Flow rate	0.30 mL min^{-1}
Injection volume	10 µL
Ionization method	ESI (Electrospray)
Ion detection mode	(-) Negative
Capillary voltage	4.5 kV
Drying gas temperature	350°C
Column temperature	40°C

E. Coli concentration was measured by diluting samples on phosphate buffer solution (PBS) and incubating on Compact EC Dry (Nissui Pharmaceutical Co. Ltd) plates for 24h at 37°C in triplicates. Blue colonies were counted and data from plates with count numbers between 30 and 150 were used for calculating the average concentration in CFU mL^{-1}.

Sampling was done every one week during the first two months and every two weeks after that. For geotextile filter and ISF effluents, a full-day (24h) sample was collected by placing 3 L plastic containers below the columns before the 9 AM discharge and collecting them the next day at the same time. Each sample was stirred gently and analyzed immediately.

3.3 RESULTS

3.3.1 Pretreatment and general performance

Table 1 shows the average quality of raw greywater and pretreated geotextile effluent, from day 31 until the last sampling. The geotextile filter removed about 70 mg L^{-1} of SS, which accounted for 62.9% of the total load. In average, 109 mg L^{-1} of COD was removed by pretreatment, 23.7% of the raw concentration. Particulate COD (P-COD) was reduced in average 46% while removal of dissolved COD (D-COD) part was only about 5.5%. Likewise, other parameters were removed more significantly in their particulate part (TN, TP). LAS removal was about 9% and E. Coli less than 1 log. TN and TP concentrations in raw greywater were usually low, in the range of 12 and 5 mg L^{-1}, respectively; small amounts in inorganic forms were detected. Removal of TN and TP was about 20 and 27%, mainly in the particulate fraction. Concentration of NH_4^+ increased slightly.

The temperatures changed significantly in the room where the ISFs were located during the operation period, which started in the beginning of summer and ended by the last month of winter; nevertheless, the performance was stable in terms of quality of effluent. During the first month the quality of the effluents increased until stabilizing (Figure 4); for the purpose of comparing performance, the average data shown for ISFs includes only the measurements after 31 days. Apparent reduction of the hydraulic conductivity was observed in all ISFs after 240 days, by the time the experiment was about to end. Accumulation of biomass was observed in the top of all ISFs and was estimated after the experiment was finished in terms of organic matter and bacterial population (data not shown). The ISFs were not subjected to backwashing or maintenance of any kind during the experimental period.

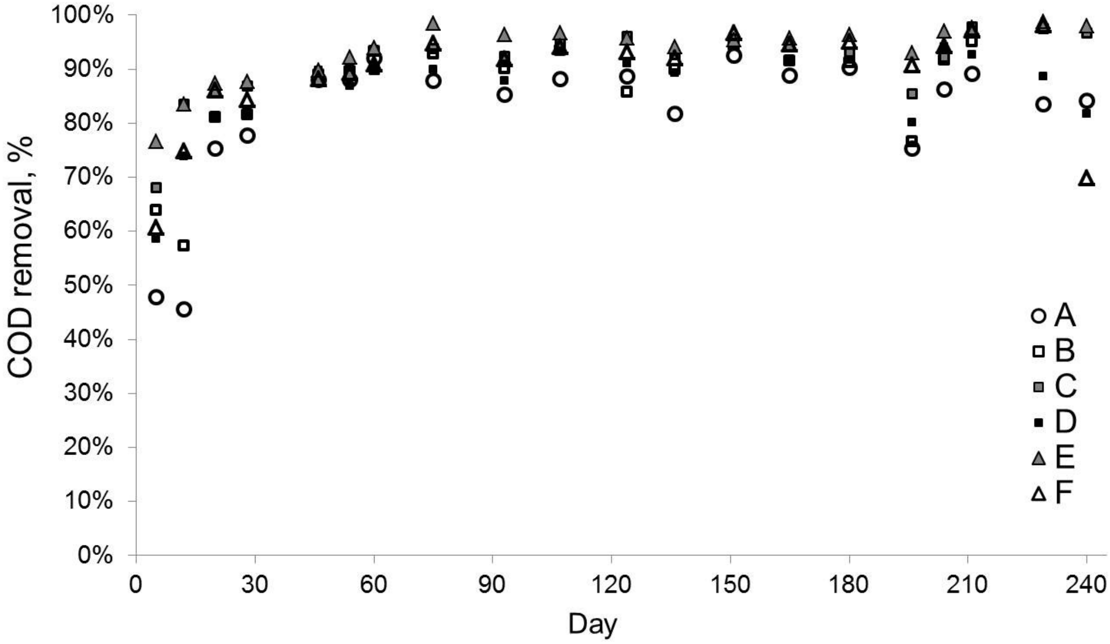

Figure 3.4 Time course of COD removal

3.3.2 Effects of depth on quality of effluent

ISFs A, B and F were used to evaluate effects of depth in a uniform layer configuration. Three of them had medium sand size (d_{10}=0.6 mm) and depths of 20, 40 and 60 cm respectively. Once the stabilization period had passed, the efficiency in removal of SS was high in all cases (97.2 to 98.4%), with concentrations of 2.65, 2.52 and 2.53 mg L^{-1}, respectively (Table 3). Concentration of COD in effluents was 61, 46 and 30 mg L^{-1}, which accounts for an average removal of 86.7, 89.9 and 93.5% from raw greywater. While the value of particulate COD was slightly higher in deeper ISFs (94.1, 96.4 and 96.5%, respectively), it was dissolved COD concentration the one that had a larger margin of difference (79.9, 84.8 and 91.6 %) (Figure 5). Removal of LAS was 91.8, 95.7 and 98.2% in average, which was a similar trend to that of dissolved COD. The log removal of E. Coli was 1.16, 1.29 and 1.59, respectively.

Table 3.3
Effect of depth in ISF effluents

		Media size d_{10}=0.6mm		
		Column A	Column B	Column F
		h=20 cm	h=40 cm	h=60 cm
SS	mg L^{-1}	2.65 ± 2.96	2.52 ± 1.64	2.53 ± 3.12
COD	mg L^{-1}	61.06 ± 24.16	46.25 ± 22.71	30.07 ± 15.16
Total-N	mg L^{-1}	5.04 ± 2.72	5.30 ± 3.41	5.32 ± 3.51
NH_4^+-N	mg L^{-1}	0.07 ± 0.07	0.04 ± 0.04	0.14 ± 0.31
NO_3^--N	mg L^{-1}	2.12 ± 2.02	2.41 ± 1.84	2.77 ± 2.48
Total-P	mg L^{-1}	1.60 ± 0.63	1.65 ± 0.67	1.61 ± 0.49
Ortho-P (PO_4^{3-})	mg L^{-1}	0.79 ± 0.26	1.04 ± 0.31	1.03 ± 0.38
LAS	mg L^{-1}	3.55 ± 2.17	1.87 ± 1.60	0.76 ± 0.52
E. Coli	log removal	1.16 ± 0.77	1.29 ± 0.74	1.54 ± 0.78

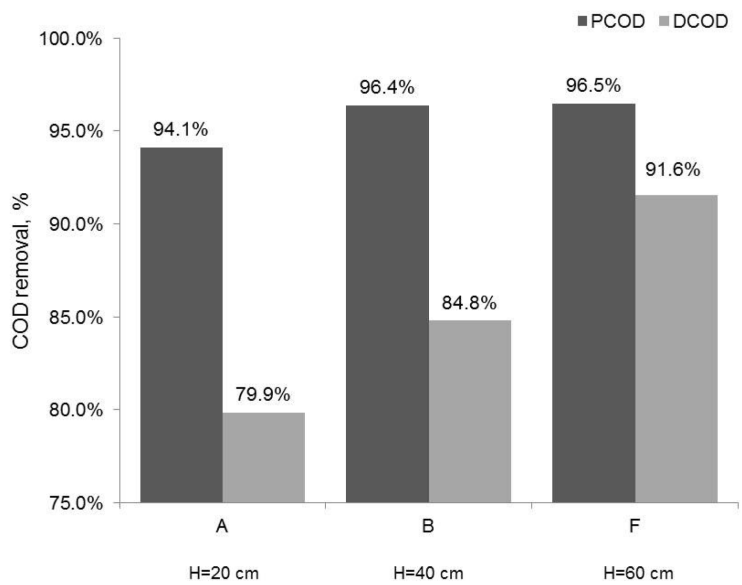

Figure 3.5 Removal of COD by depth

3.3.3 Effects of media size on quality of effluent

ISFs B, C, D and G were used to compare the effects of different sand size in shallow filters (40 cm). As explained in the previous section, column B contained only medium sand size. Column C was designed with the bottom half using fine sand (d_{10}=0.3mm) and column D with a top half using coarse sand (d_{10}=0.9 mm). ISF G was operated in a separated experiment for the same period length, and it combines coarse sand in top and fine sand in bottom.

SS concentration in effluents was 2.52, 1.90, 2.96 and 2.22 mg L^{-1}; this is a removal of 97.7, 98.3, 97.3 and 97.9% from raw concentration, respectively (Table 4). COD removal was 89.9, 93, 89.5 and 91.3%. Particulate COD was removed 96.4, 96.4, 94.7 and 96.8% while the dissolved fraction was reduced in average 84.8, 90.4, 83.9 and 86.5% (Figure 6a). Concentration of LAS in effluents was 1.87, 0.90, 1.35 and 0.89 mg L^{-1}, an efficiency of 95.7, 97.9, 96.9 and 97.8%. E. Coli reduction was 1.3, 1.6, 1.3 and 1.41 log.

Table 3.4
Effect of media size in quality of effluents

		Depth h = 40 cm			
		Column B	Column C	Column D	Column G
		0-40: d_{10}=0.6	0-20: d_{10}=0.6 20-40: d_{10}=0.3	0-20: d_{10}=0.9 20-40: d_{10}=0.6	0-20: d_{10}=0.9 20-40: d_{10}=0.3
SS	mg L^{-1}	2.52 ± 1.64	1.90 ± 1.90	2.96 ± 3.11	2.14 ± 1.46
COD	mg L^{-1}	46.25 ± 22.71	32.19 ± 18.73	48.13 ± 20.92	34.94 ± 9.16
Total-N	mg L^{-1}	5.30 ± 3.41	4.36 ± 2.94	5.18 ± 3.23	-
NH_4^+-N	mg L^{-1}	0.04 ± 0.04	0.02 ± 0.03	0.06 ± 0.07	-
NO_3^--N	mg L^{-1}	2.41 ± 1.84	2.39 ± 1.91	1.98 ± 1.79	-
Total-P	mg L^{-1}	1.65 ± 0.67	1.56 ± 0.66	1.76 ± 0.64	-
Ortho-P (PO_4^{3-})	mg L^{-1}	1.04 ± 0.31	0.96 ± 0.28	0.82 ± 0.27	-
LAS	mg L^{-1}	1.87 ± 1.60	0.90 ± 0.51	1.35 ± 0.87	0.76 ± 0.39
E. Coli	log rem.	1.29 ± 0.74	1.61 ± 0.78	1.31 ± 0.88	1.41 ± 0.20

ISFs E and F were used to compare the effect of layering at depth 60 cm. As mentioned previously, F had a single layer of medium sand, while E had three 20-cm layers of coarse, medium and fine media, respectively. SS in effluents was 1.24 and 2.53 mg L^{-1}. These columns obtained the highest removal of organic matter, COD concentration was 20.38 and 30.07 mg L^{-1} (Table 5). Dissolved COD was 17.17 and 21.46 mg L^{-1}, while PCOD was 1.79 and 7.15 mg L^{-1}. (Figure 6b) LAS concentration was 0.74 and 0.76 mg L^{-1}, which accounts for 98.3 and 98.2%. The highest removal of E. Coli by any ISF was achieved by column E with an average of 2.22 log, while F removed only 1.54.

Table 3.5

Effect of media size in quality of effluent at 60 cm depth

		Depth h = 60 cm	
		Column E	Column F
		0-20: d_{10}=0.9 20-40: d_{10}=0.6 40-60: d_{10}=0.3	0-60: d_{10}=0.6
SS	mg L^{-1}	1.21 ± 1.45	2.53 ± 3.12
COD	mg L^{-1}	20.38 ± 12.56	30.07 ± 15.16
Total-N	mg L^{-1}	4.92 ± 2.76	5.32 ± 3.51
NH_4^+-N	mg L^{-1}	0.01 ± 0.01	0.14 ± 0.31
NO_3^--N	mg L^{-1}	3.16 ± 2.62	2.77 ± 2.48
Total-P	mg L^{-1}	1.70 ± 0.55	1.61 ± 0.49
Ortho-P (PO_4^{3-})	mg L^{-1}	1.24 ± 0.39	1.03 ± 0.38
LAS	mg L^{-1}	0.74 ± 0.53	0.76 ± 0.52
E. Coli	log removal	2.22 ± 0.99	1.54 ± 0.78

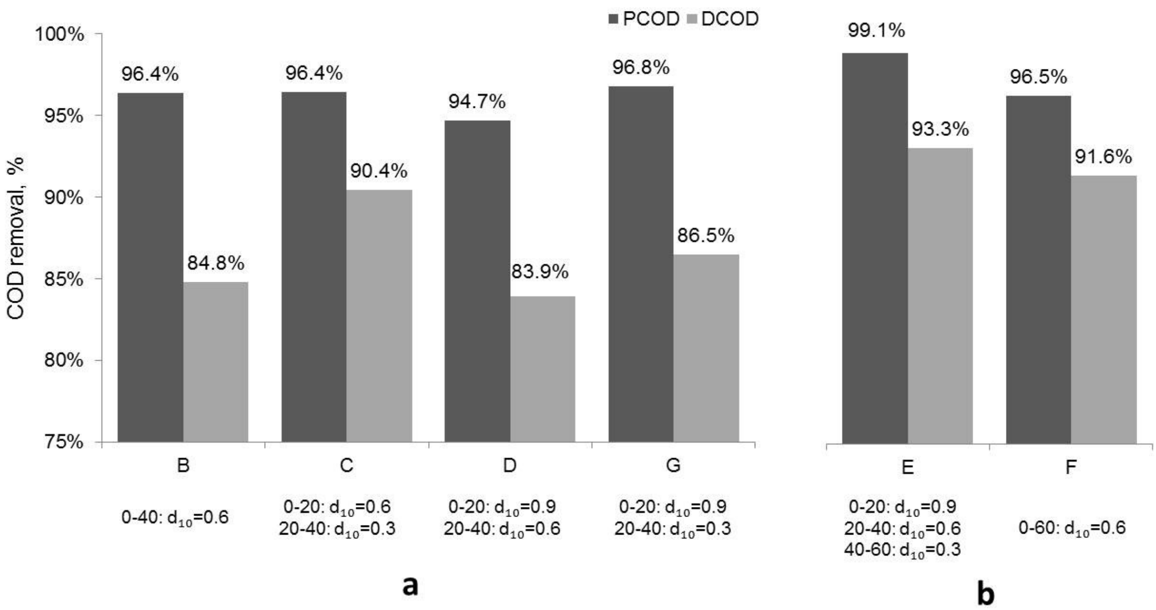

Figure 3.6 Effect of layering on removal of COD

3.3.4 Nitrogen and phosphorus

ISFs are basically aerobic systems, and therefore no denitrification was expected to occur. Figure 7 shows the contents of N in influents and effluents. Largely, the particulate part of N was removed, while dissolved form was transformed from organic forms to NO_3^{-}. In general, depth increased the efficiency of nitrification. P removal followed a similar trend (Figure 8), the particulate part was captured and the dissolved part passed through the columns.

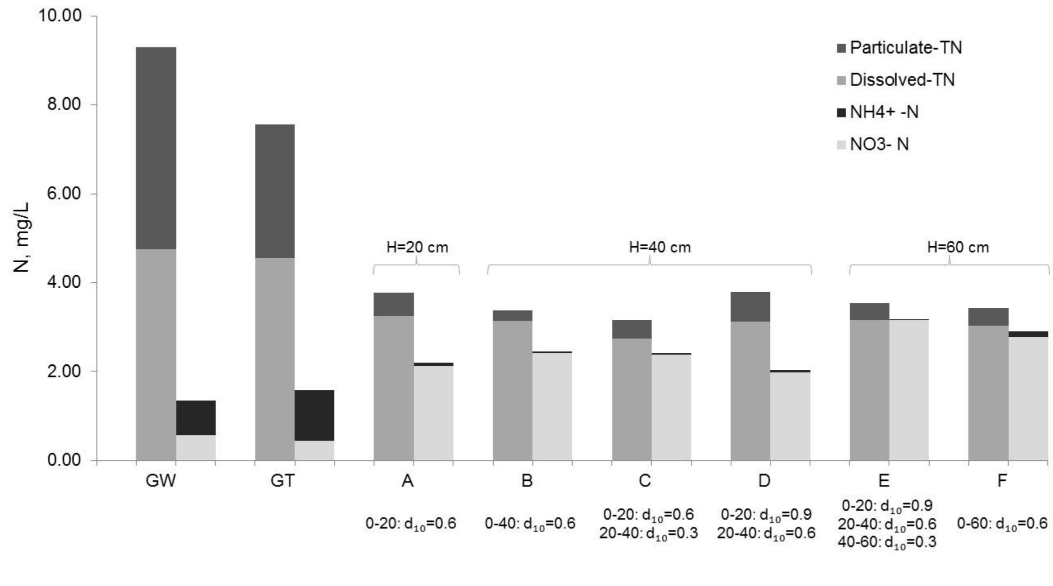

Figure 3.7 Removal of N

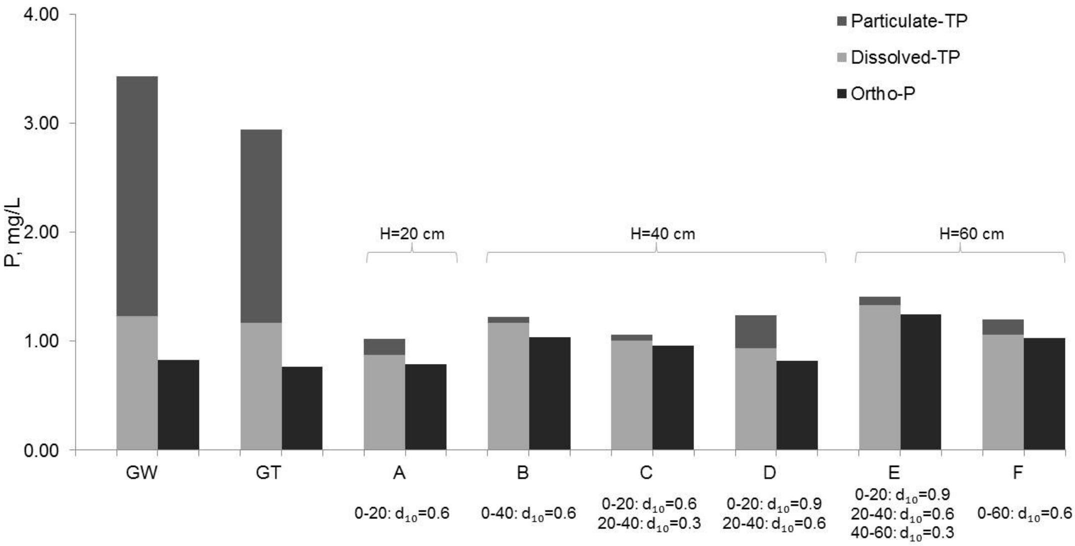

Fig 3.8 Removal of P

3.4 DISCUSSION

The quality of raw greywater had a relative variability despite strictly using the same volume of constituents in each preparation. This could be due to the variable type of clothes used in laundry and variations in human body waste when taking shower. Compared to other studies, the quality in terms of organic matter and SS was in the middle range, while low contents of nutrients N and P were observed. The average concentration of LAS in the experimental greywater (about 43 mg L^{-1}) could be considered as high, since it has been usually detected before in lower ranges (Almqvist & Hanæus 2006); however, most of those studies focus on urban scenarios with large availability of water.

The geotextile filter removed SS and COD ranging from 11 to 84% and 3 to 43%, respectively; although some organics in dissolved form were captured, it was mainly the particulate part. Such a large variation in efficiency is due to the progressive clogging process of the filter itself, as the accumulated loaded influent grows and the pore size is reduced. The purpose of the pretreatment is to extend the performance of ISFs as in Charchalac Ochoa *et al.* (In press) by controlling the particle size of SS in influent to the columns. Besides SS, hair and lint, on occasions other types of materials were captured by the geotextile, including insects, dust, etc. In other words, since no pretreatment like grease trap or septic tank is considered in this simple setup, the role of geotextile filter is essential to avoid early irreversible failure of the system. Additionally, since the kitchen sink greywater was not included, problems from oils and fats were not observed.

In general, the performance of the ISFs achieved high quality in effluents, even in the shallowest system. It was hypothesized that, by using coarser media (d_{10}=0.9 mm) in the top layers (D and E), a longer time would be required for its pores to become clogged but it could also have a detrimental effect on the quality of effluent. However, the failure of the systems, although not measured quantitatively, seemed to start to occur after day 240 for all systems regardless of media size in the top layer. On the other hand, the use of fine media (d_{10}=0.3 mm) was supposed to provide higher quality of effluent but would be easy to clog and therefore it was limited to be used only as bottom layer of a composite ISF with the purpose of polishing the effluent (C, E and G). It was assumed that the larger particles that could cause "fast" clogging by deposition would be retained in the top of either the fine or coarse media of each ISF.

ISFs B and F showed the benefit of larger depth for a column with medium size sand in removal of dissolved organic matter. Removal of solids did not show significant difference and the concentration of SS in effluents was in all cases below the target 3 mg L^{-1}. Similarly, the concentration of particulate COD in effluent had negligible differences, but the difference was noticeable in dissolved fraction. Concentration of LAS in effluent had a similar trend to that of dissolved COD, but even in the 20 cm depth more than 90% of LAS were removed. In general, it is possible to observe that the shallowest system with conservative medium sand can fulfill the requirements for surfactants and SS. However, the difference in dissolved COD could be due to incomplete biodegradation of organics and could potentially allow bacterial regrowth in the tubes or emitters of irrigation systems.

In the comparison of the four columns with 40 cm depth, the inclusion of fine sand in the bottom resulted in a better performance (C and G), noticeable in the average removal of SS, dissolved COD and LAS. Although the inclusion of coarse sand in the top did decrease the removal by 0.4, 0.5 and 1.2% for each parameter, the effect was smaller than fine sand layer, which improved the efficiency by 0.6, 3 and 2.2%.

Columns F and E could be considered as the addition of extra 20 cm of depth with medium and fine sand to ISFs B and D, respectively. In the case of F, SS removal did not improve, although it was already high quality; in the case of COD, the efficiency improved by about 3.6%. For E, the additional fine sand layer increased the SS removal by 1.6% and COD by 6.1%. LAS were also removed efficiently and in a relatively higher ratio compared to dissolved COD. This is probably because LAS are readily biodegradable in aerobic conditions. The final concentrations in effluents at this depth were always below 1 mg L^{-1}, and therefore far below the target set for this study. As a summary, it is clear the significant benefit of smaller sand, without sacrificing lifetime.

The inclusion of fine sand improved the effluents to high quality and moreover, if standard deviations are observed, more stable values of SS and COD are obtained when using fine sand, which also means those configurations are more resistant to variations in influent quality.

The concentration of indicator E. Coli in greywater was set to 5 log CFU mL^{-1}. Pretreatment geotextile captured 0.4 log CFU mL^{-1} in average, but with a large range of variation depending on the conditions of the filter. In general, the total removal of *E. Coli* by ISFs was low, ranging from 1.3 to 2.2 log, which left a concentration of E. Coli in effluent far beyond the minimum requirement for unrestricted reuse. Better removal rates were observed in deeper ISFs or the ones including a fine layer in the bottom. This low efficiency could be due to the short retention times given by the intermittent high-volume discharge pattern. A relative improvement of the removal was observed towards the end of the operation of the columns, which might be associated to the longer surface infiltration time and therefore the slower transit through the media as well.

The maximum depth in this experiment was considered to be only 60 cm, since the treatment beyond this depth is considered to provide less significant benefits in quality and our approach seeks to reduce the required depth/material for the minimum quality and avoiding too much hydraulic head loss that would force the need for pumping or other type of transportation for the effluent reuse. Additionally, the quality of effluent can also be improved through factors like the characteristics of media; both size and UC may have an impact on the performance of the ISFs (Darby *et al.* 1996), therefore low UC were considered in this experiment.

Implementation of ISFs for reuse of effluents is challenged by two seemingly excluding challenges: either low maintenance/small-footprint systems or more complex schemes with high levels of biological disinfection (Leverenz *et al.* 2009), hinting that one condition would omit the other. This is based on the idea that the adaptation of complex disinfection technologies to small scale is not viable added to the fact that the design should be simple for onsite systems. In other words, a sustainable system would be one where the potential users should not have to intervene periodically or perform laborious maintenance tasks.

Pathogen removal seems to be the conditioning parameter for reducing the depth and size under the proposed HLR and number of doses. Two possible strategies could be followed: either add another step for treatment or disinfection or limit the type of irrigation patterns to be used with the effluent. The usage of cheap ceramic eco-filters (van der Laan *et al.* 2014) or shallow ponds for solar radiation exposure (SODIS)

(Pansonato *et al.* 2011) could be feasible as long as the quality of effluents is high enough in terms of solids and turbidity, something achievable by ISFs. On the other hand, the high quality of effluents in terms of SS, especially when using fine media, allows the use of subsurface irrigation systems that have the lowest need for human contact with the effluent. Moreover, ISFs effluents could be limited for handling when certain conditions are fulfilled, as proposed by Rodda *et al.* (2011). For example, if one of the members of the family suffers a gastrointestinal disease then reuse of treated greywater should be banned or, if crops that are eaten raw are irrigated with effluent then usage of treated greywater should be stopped for a period of time before harvesting. Considering the variety of alternatives, it should not be impossible to implement a feasible scheme to reuse ISFs effluents with minimum safety.

3.5 CONCLUSIONS

- Pretreatment of domestic greywater by geotextile filters ensured a performance of at least 8 months without backwash or any maintenance to ISFs with medium or coarse media in the top layer at the hydraulic discharge of 16 cm d^{-1}.

- Most of the treatment occurs in the top 20 cm layer, however, by increasing the depth of an ISF the removal of SS and dissolved organic matter can be improved to levels that could reduce the risk to the performance of irrigation systems.

- Layering with uniformly graded coarser media (d_{10}=0.9 mm) in top did not significantly affect the lifetime of ISFs or the quality of effluent.

- Layering with fine media (d_{10}=0.3 mm) in bottom improved the removal of dissolved organic matter, suspended solids and E. Coli.

- Concentration of LAS is below 3.55 mg L^{-1} at depths of just 20 cm (91.8%). Implementation of a polishing layer of fine sand reduces the concentration to less than 1 mg L^{-1}, 97.9% of total load.

- emoval of E. Coli was below the required level for intensive handling use of effluent. However, several measures can be used to avoid health issues.

Generally, the ISFs performed with a potential enough to treat relative large volumes (160 L m^{-2} d^{-1}) of greywater to high quality levels in terms of organic and suspended contents that would allow the implementation of high-efficiency irrigation systems and therefore improved production capacity.

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Chapter 4

INFLUENCE OF HYDRAULIC LOADING RATE ON TREATMENT OF GREYWATER BY SIMPLE STRATIFIED INTERMITTENT SAND FILTERS

4.1 INTRODUCTION

The overall objective of this Chapter was to evaluate the effects of hydraulic loading rate on a simple shallow stratified ISF in achieving the required quality of the effluent for greywater to be reused in irrigation regarding the targets set previously.

Generally, ISFs are used as a secondary treatment and their lifetime and performance depend on several factors: hydraulic loading rate (HLR), size and uniformity of media, frequency and volume of doses, the efficiency of the primary treatment, etc. (Darby *et al.* 1996; Winter & Goetz 2003; Rodgers *et al.* 2010). HLR, inversely proportional to the surface area of the bioreactor, will determine its lifetime. Furthermore, although the ISF systems are resilient to variations in the flow, it is likely that the quality of the effluent will decrease when increasing the loads. Therefore, it is needed to evaluate the performance of ISFs under different HLRs to assess its efficiency and limitations in reclamation of greywater for irrigation.

4.2 MATERIALS AND METHODS

4.2.1 Intermittent sand filters assembly

A geotextile filter system (GT) designed to be in-line with the ISFs was used as pretreatment to remove SS and lint from raw greywater before being discharged to the sand media (Figure 1a). Geotextile fabric model 4101N (polypropylene nonwoven needle-punched) by TOYOBO CO Ltd, with apparent opening size of 0.12 mm, thickness 1.4 mm and weight 106 g m^2, was chosen due to the availability in the experimental location. The assembly for the filter consisted of a short section (10 cm) of a 140 mm diameter PVC pipe coupled to a 140 x 75 mm PVC reducing connector. A circle-shaped piece of geotextile (Figure 1a) of about 20 cm diameter was stretched tightly between the pipe section and the coupling as shown in Figure 1b; the tight fitting of the tubing and adaptor ensured for the greywater to flow only through the fabric (Figure 1c).

The geotextile filter was replaced with a new one when it became clogged (i.e. incomplete infiltration after 24 h), which occurred between 5 to 16 days, depending on the HLR regime. 20 cm were left between the sand and the bottom of the GT assembly to avoid mix-up or interference in the interpretation of clogging either in media or in the geotextile if ponding occurred.

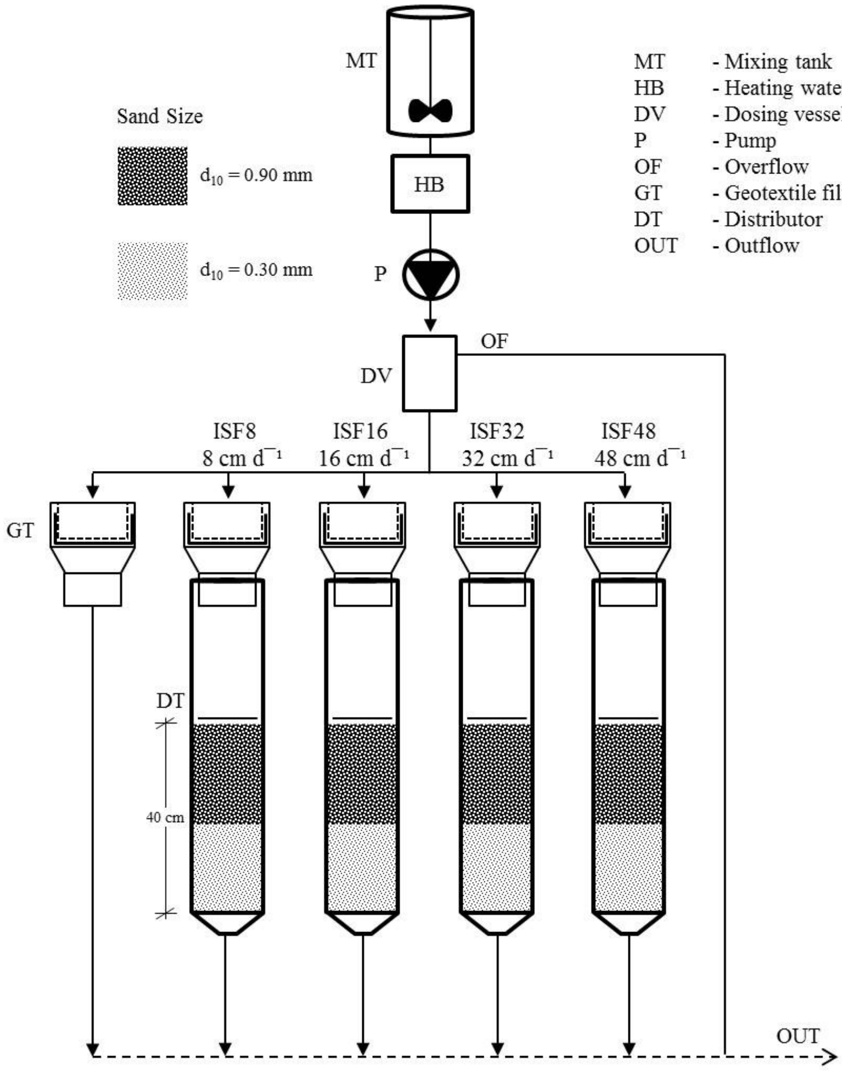


Figure 4.1 ISF experimental setup

Four sand filters (ISF8, ISF16, ISF32 and ISF48) were constructed with transparent cylindrical PVC pipes and accessories (Figure 2). Transparent materials were used to allow observation of the accumulation of solids and growth of biomass inside the filter. Each pipe section had an inner diameter of 13.1 cm and total depth of 60 cm. The bottom drainage consisted of a 5 mm-thick flat plastic punched sheet covered with a stainless steel mesh sheet with 0.2 mm sized openings. The ISFs were inside a chamber which was covered with black plastic to avoid penetration of sunlight while the room temperature was controlled to avoid going below 20°C during the winter time. The experimental period was 321 days between October 2013 and August 2014.Depth of media was 40 cm, consisting of two 20-cm layers of coarse and fine sand with d_{10}=0.30 mm and d_{10}=0.90 mm, respectively. The sand was obtained from a company that supplies material typically used in large sand filters of local wastewater treatment plants; it was washed, sieved and graded to obtain a uniformity coefficient of UC_{30}=1.57 and UC_{90}=1.2, respectively (Figure 3).

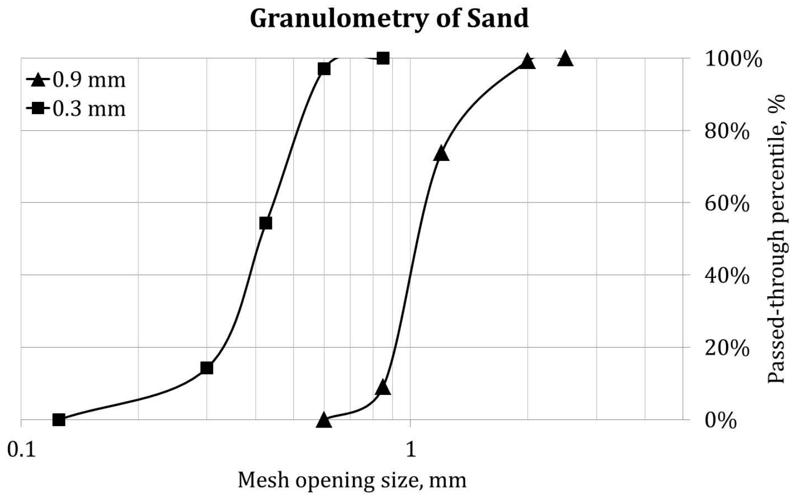


Figure 4.3 Granulometry of media

4.2.2 Greywater characteristics and loading

The greywater used in this study was a mixture of shower and laundry effluents (60:40 in volume), excluding kitchen sink greywater as suggested by Maimon *et al.* (2014). Greywater from shower and washbasin was collected from a shower room located in the laboratory premises; this was planned to include the organic waste originated from human body. Constituents included shampoo (Unilever LUX, 5 g 30 L^{-1}), conditioner (Shiseido TSUBAKI, 5 g 30 L^{-1}), body soap (5 g 30 L^{-1}) and toothpaste (Sunstar GUM, 3 g 30 L^{-1}). Before the preparation, each constituent was weighed with a precision of 0.01 g in separate plastic containers. Then shower was taken by one person using the contents of the plastic containers. The shower drain was connected to three semitransparent water tanks marked to a 20 L level that received the effluent, so the volume of accumulated greywater was collected with relative accuracy. Laundry greywater was prepared by washing three to four pieces of clothes in a washing machine using 25 g of powder detergent (Unilever OMO) per 40 L of water; this detergent was chosen since linear alkylbenzene sulfonates (LAS) are the active surfactants, one of the targets of this study.

Escherichia Coli NBRC 3301 strain was used as indicator of enteric bacterial pathogens. Pure stock of NBRC 3301 was first activated by 24 h incubation in triptic soy broth (TSB) in 37°C water bath agitated at 116 rpm, followed by streaking on a triptic soy agar (TSA) plate and incubated for 24h at 37°C. Subsequently a single colony was transferred with an inoculation loop to 100 mL of TSB and incubated for 4 h in a 37°C water bath at 116 rpm. The solution was poured to previously prepared 100 L of fresh greywater. By this method, the concentration in the greywater was around 1.0×10^5 CFU mL^{-1}.

After preparation, both types of greywater were transported, mixed in the volume ratio indicated and stored in a tank located inside a refrigerator at 3-4°C under constant stirring to maintain a homogeneous particle suspension. Fresh greywater was prepared every five days. Typical temperature of greywater is in the range of 18 to 38°C (Eriksson *et al.* 2002); therefore, the feeding tube from the mixing tank to the ISFs passed through a heated water bath that brought greywater to a temperature of between 17-20°C when reaching the dosing vessel. The chemical characteristics of raw greywater and effluent from GT are shown in Table 1. In general, the quality of the experimental greywater was in the middle range for raw greywater (Almeida *et al.* 1999; Morel & Diener 2006).

Greywater hydraulic loading rates (HLR) of 8, 16, 32 and 48 cm d^{-1} were applied to each ISF, respectively. The total daily volume was split into three equal daytime doses (9 AM, 12 PM and 6 PM) corresponding to the theoretical morning, noon and evening peak time for water use (Funamizu *et al.* 2002), therefore a single dose was of 2.66, 5.33, 10.66 and 16 cm, respectively. The greywater was pumped by peristaltic pump to a dosing vessel with capacity to measure either 381.4 or 762.8 cm^3 (2.66 or 5.33 cm dose). The discharge was controlled by a valve above the GT assembly and delivered through five pulses of 7 seconds each, separated by intervals of 53 seconds between one another, totaling 5 minutes per dose. ISF8 received one dose of 381.4 cm^3, while ISF16, ISF32 and ISF48 received one, two and three doses of 762.8 cm^3, respectively. Each volume was supplied in a span of 5, 5, 10 and 15 min, respectively. SS loading rates were 8.42, 16.85, 33.69 and 50.54 g m^{-2} d^{-1}; while for COD they were 33.11, 66.21, 132.42 and 198.64 g m^{-2} d^{-1}, respectively.

4.2.3 Sample analysis

Influent and effluent samples were analyzed for suspended solids (SS), total and dissolved chemical oxygen demand (COD), biodegradable organic carbon (BDOC), linear alkylbenzene sulfonates (LAS) and *Escherichia Coli* NBRC 3301 strain as indicator of enteric pathogens.

SS was determined by Standard Methods (American Public Health Association *et al.* 1989). COD was measured by using HACH kit (Method 8000) and the HACH DR2800 Spectrophotometer. For measurement of dissolved fractions, 100 mL (greywater and geotextile effluent) and 300 mL (ISFs effluents) samples were filtered with prewashed ADVANTEC GB-140 fiber glass filters (pore size 0.4 µm) with suction filtration equipment. Particulate fractions were estimated as the difference between total and dissolved measurements.

BDOC was determined by measuring the reduction in dissolved organic carbon (DOC) of diluted samples stored at 20°C in BOD vessels after 7, 14 and 28 days. DOC was measured by Shimadzu TOC-V_{CSH} analyzer.

Concentration of LAS (C10 to C14) was determined using liquid chromatography mass spectrometry (LC-MS) based on Managaki *et al.* (2005) and (Ushijima *et al.* 2013). The samples were cleaned by solid phase extraction process (SPE) with a BOND ELUTE® PPL cartridge using the same method as (Charchalac Ochoa *et al.* In press). LAS C8 trace recovery standard surrogate was added at 0.01 mg L^{-1} concentration. All samples were diluted to a concentration in the range of 0.01 to 0.25 mg L^{-1}, where linear relationship was observed in the chromatographic peaks. Standard LAS solution (C10 to 14) and recovery standard C8 reagent were obtained from WAKO Industries (> 99% purity).

E. Coli concentration was measured by diluting samples on phosphate buffer solution (PBS) and incubating on Compact EC Dry (Nissui Pharmaceutical Co. Ltd) plates for 24h at 37°C in triplicates. Blue colonies were counted and data from plates with count numbers between 30 and 150 were used for calculating the average concentration in CFU mL^{-1}.

Sampling was done every week during the first two months and every two weeks after that. For geotextile filter and effluents from ISFs, a full day composite sample was collected by placing plastic containers at the bottom of the drainage just before the 9AM discharge and removed 24h after. Each sample was stirred gently and analyzed immediately.

4.3 RESULTS AND DISCUSSION

4.3.1 Pretreatment and general performance

Table 1 shows the average quality of raw greywater and pretreated geotextile effluent, from day 31 until the last sampling. The geotextile filter removed about 46 mg L^{-1} of SS, which accounted for 43.1% of the total load. In average, 78 mg L^{-1} of COD were removed by pretreatment, 18.9% of the raw concentration. Particulate COD was reduced in average 36.4% while removal of dissolved fraction was only about 4.4%. LAS removal was about 5% and E. Coli less than 1 log. BDOC showed small increases from GW to GT, in the range of 15, 11 and 5%, for 7, 14 and 28 day measurements. The HLR for the GT samples used as reference was 16 cm d^{-1}, and it was assumed that the overall removal during the lifetime of a geotextile sample are the same, although at different HLRs the removal rates probably have small variations.

Table 4.1

Characteristics of raw greywater and geotextile effluent

	SS	COD	LAS	E. Coli	BDOC7	BDOC14	BDOC28
	mg L⁻¹	*mg L⁻¹*	*mg L⁻¹*	*cfu mL⁻¹*	*mg L⁻¹*	*mg L⁻¹*	*mg L⁻¹*
Greywater *(N=17)*	105.3±24.4	414.7±48.7	37.4±11.1	5.0±0.6	18.7±11.1	26.2±10.2	30.1±11.5
GT Effluent *(N=17)*	59.9±17.8	336.2±42.2	35.5±10.6		21.6±8.9	29.0±7.1	31.4±8.6

The experiment lasted for 321 days. During the first month the quality of the effluents increased until stabilizing (Figure 4). The average data shown for ISFs includes only the measurements after day 31 until the last sampling before failure occurred for each column. Reduction of the apparent hydraulic conductivity was observed in all of the ISFs during the experimental run. Clogging occurred in cases ISF16, ISF32 and ISF48, at day 249, 149 and 115, respectively. The ISFs were not subjected to backwashing or maintenance of any kind during the experimental period.

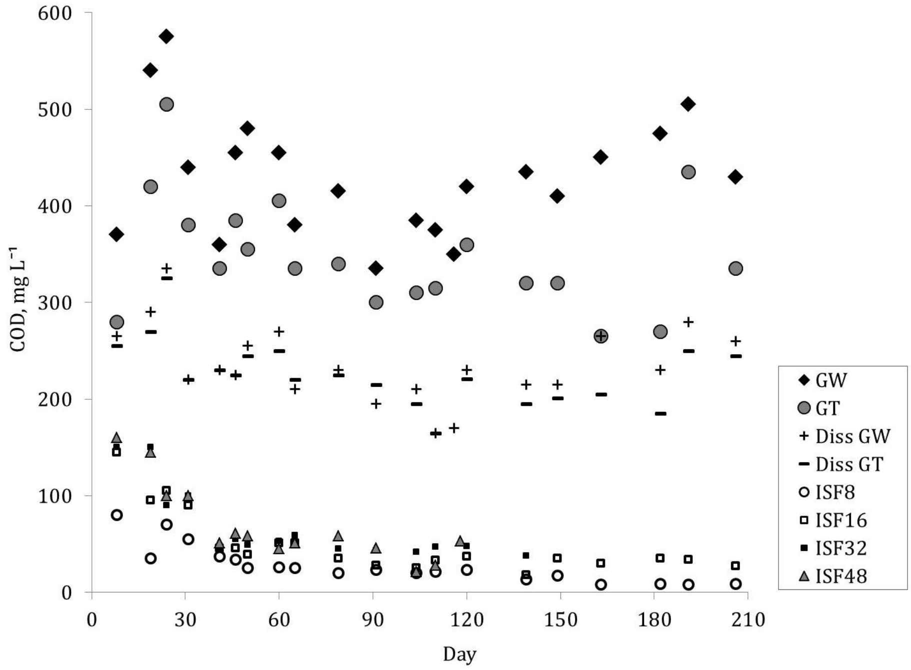


Figure 4.3 COD Timecourse

Table 2 shows the average quality of effluents from each ISF during their run until the last sampling before failure. In the cases of ISF16 and ISF48, samples taken on the same day of stopping the experiment were not included for the weighted average since it was considered that the functional period of the system had already ended. Besides the incomplete infiltration of a daily dose, a severe increase in COD and SS of the effluent was observed.

Table 4.2

Characteristics of effluents

	HLR	SS	COD	LAS	E. Coli	BDOC7	BDOC14	BDOC28
	cm d^{-1}	*mg L^{-1}*	*mg L^{-1}*	*mg L^{-1}*	*log removal*	*mg L^{-1}*	*mg L^{-1}*	*mg L^{-1}*
ISF8	8	0.8±1.0	19.1±8.9	0.2±0.1	2.0±0.4	0.7±0.5	1.5±1.3	2.2±1.7
ISF16	16	2.1±1.5	34.9±9.2	0.8±0.4	1.4±0.2	2.2±1.4	3.4±1.6	4.5±2.0
ISF32	32	4.6±2.2	47.7±5.8	0.7±0.6	1.5±0.5	2.9±1.5	4.3±1.1	5.3±1.5
ISF48	48	4.5±5.5	47.2±12.4	0.7±0.5	1.4±0.3	2.3±1.3	3.9±1.8	4.9±2.3

ISF8 and ISF16 were effective to reduce SS to levels below the required target, while for ISF32 and ISF38 the value was about 50% higher (3 mg L^{-1}). As expected, in terms of removal of organic matter, the lower HLR columns performed better in the removal of COD and BDOC.

Comparing the quality of effluents (Table 2), it is clear that by reducing the daily discharge the quality of effluent improved. This is likely because of the longer retention time inside the ISF. ISF8 and ISF16 particularly achieved SS concentration below the target 3 mg L-1, and BDOC that progressed through time to concentrations below 1 mg L-1 (i.e. BDOC starvation) from month 3 and month 5, respectively. Concentration of COD, both cases particulate and dissolved, correlated to the discharge rate. LAS target concentration was easily achieved by all four configurations, hinting to a fast adsorption and degradation rate for a relative high concentration of surfactants (40.5 mg L-1).

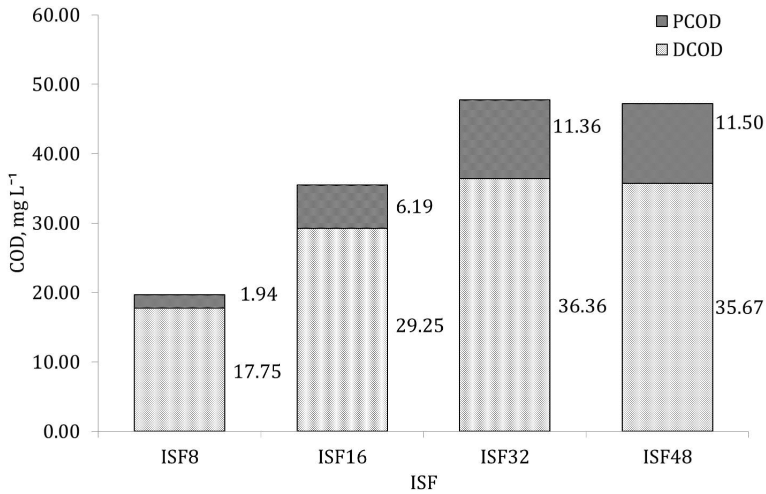
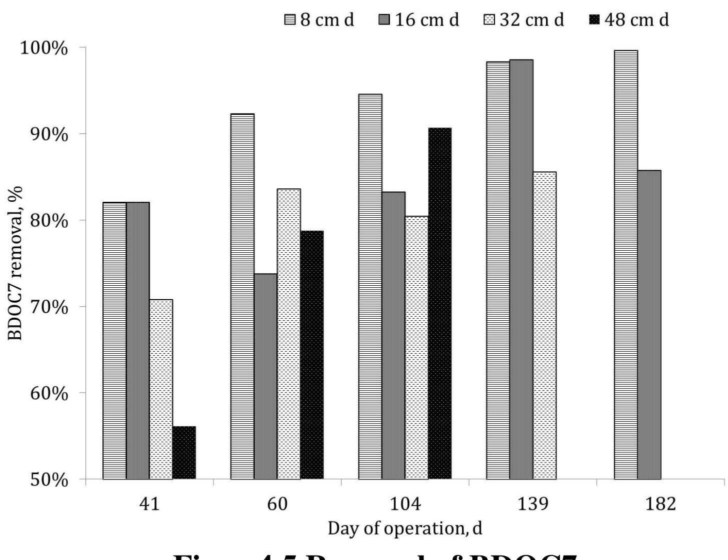


Figure 4.4 Removal of COD



Figur 4.5 Removal of BDOC7

On the other hand, removal of E. Coli remained low in all cases. ISF8 removed about 2 log units, while for the other three the removal oscillated between 1.4 and 1.5 irrespectively of the daily discharge. Capture by adsorption seems to be limited to the short contact time of influent in the bioreactors. This situation confirms the need to include an additional disinfection step or specific conditions for reuse of effluent in terms of type of crop and type of irrigation system.

The total filtered volume by the end of operation was 20.1, 39.8, 47.7 and 57.6 m3 m-2 by each unit. This shows that the ISFs with larger daily discharge had a higher overall total capacity before failure, although ISF8 was still in operating conditions.

Table 4.3
Total filtered volumes and removals before failure/stopping

	Operating days	Daily discharge	Total filtered volume	Removal	
				SS	COD
		L m^{-2} d^{-1}	m^3 m^{-2}	*kg* m^{-2}	*kg* m^{-2}
8 cm d^{-1}	321	80	25.68	1.42	7.41
16 cm d^{-1}	249 *	160	39.84	2.20	11.49
32 cm d^{-1}	149 *	320	47.68	2.64	13.75
48 cm d^{-1}	115 *	480	55.2	3.06	15.95

* clogged

TSS and TCOD removed by each ISF system (including GT) (In/Out concentration × Operation time) are as follows: 1.42, 2.20, 2.64 and 3.06 kg m^{-2}; 7.41, 11.49, 13.75 and 15.95 kg m^{-2}. Overall, despite the higher quality of effluent in the case of ISF8 and ISF16, if the operating time is taken into equation, the ISFs with higher hydraulic discharge had a higher total capacity for filtration before failure.

4.4 CONCLUSIONS

Increasing of the hydraulic daily discharge (i.e. reduction of surface area) reduced the lifetime of ISFs and marginally reduced the quality of effluent in terms of SS and dissolved organic matter. Although higher SS was observed, it was mostly non-settleable particles, and therefore less likely to cause immediate damage to irrigation systems. In contrast, the total filtering capacity of the systems was higher when greater daily discharges were used. Low removal of E. Coli was observed a maximum of 2 log units under the experimental conditions (8 cm d-1), so additional measures must be considered for safe reuse of LLGW treated by ISF.

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Chapter 5

REMOVAL OF UV FILTER COMPOUNDS FROM GREYWATER BY INTERMITTENT SAND FILTRATION

5.1 INTRODUCTION

As mentioned in previous introduction, the reuse of wastewater is recognized as essential for a large population worldwide that could be under water deficit risk, especially in areas that depend on agriculture. Domestic greywater is a potential extra source of water in future, but its continuous reuse involves potential risks to health and the environment. However, treatment systems have focused on achieving discharge/reuse levels concerning to standard parameters (Revitt et al., 2011); in this regard, several other associated risks should be considered, including the discharge of emergent micropollutants and other xenobiotic organic compounds –XOCs– to environment (Hernandez et al., 2011), especially the ones with potential to enrich in bio solids or soil. The importance of simple technologies for treatment of wastewater as a barrier to remove specific XOCs from reaching environment has been recognized (Revitt et al., 2011).

With knowledge of ultraviolet rays (UV-A and UV-B type) induced skin damage, sunscreen products containing UV filter compounds have become more popular. UV compounds are among many of the emergent pollutants that might increase in concentration in greywater effluents; among these chemicals, designed to protect human skin from solar UV radiation and used in sunscreen products, many are of hydrophobic nature, which increases its potential to bio accumulate and have been found in environmental and biota samples.

There are two types of commercial products:

- Primary sunscreens: intended to protect skin from sunlight.
- Secondary sunscreens: primary use different to skin protection (moisturizing, cosmetic, cleansing products).

Two types of compounds

- Organic: Absorpting UVR Energy
- Inorganic: Reflecting and difusing UV Rays

5.1.1 Adverse effects

UV filter compounds are becoming widespread and used in common cosmetic and skin products (Balmer et al., 2005). They have been detected in water bodies (Bratkovics et al., 2011) and sludge (Kameda et al., 2011) and in tap water in trace amounts. Additionally, some of the most common ones are known to be toxic to biota (Fent et al., 2010, Coronado et al., 2008, Schmitt et al., 2008)

5.1.2 Objective

The same intermittent sand filters equipped with geotextile filters used in Chapter 3 were evaluated for the removal of UV compounds. The objective of this Chapter is to evaluate the performance of ISFs with different physical characteristics to remove UV filter compounds from greywater.

5.2 MATERIAL AND METHODS

5.2.1 Selected UV filter compounds

Four organic UV filter compounds were selected to be evaluated based on type, market use and the hydrophobic/hydrophilic characteristics (Table 5.1).

Table 5.1 Selected UV Filter Compounds

Type	Compound	CAS No.	MW(g/ mol)	LogKow	Max % *
Aminobenzoic acid	4-p-Aminobenzoic acid (PABA)	150-13-0	137.14	0.83	15%
Benzophenones	Benzophenone 3 (BP3)	131-57-7	228.24	3.79	6%
Cinnamate	Ethylexyl methoxycinnamate (OMC)	5466-77-3	290.4	5.8	7.50 %
Photostabilizer	Octocrylene (OC)	6197-30-4	361.49	7.35	10%

*Standards form USDA

Table 5.2 Solubility of UV filter compounds

	Water Solubility (mg/L)			
	Based on Kow	Based on Fragments	Experimental	Current Experiment
PABA	16830	5539.5	6110	
BP3	68.56	2295.4	-	22.60
EHMC	0.1548	0.1432	-	0.45
OC	0.003808	0.055056	-	0.28

Table 5.3 Volatilization and Adsorption Potential

	Log Kow	Hc	Hc/Log Kow	Volatilization Potential	Adsorption Potential
PABA	0.83	1.86E-11	2.24E-11	Low	Low
BP3	3.79	1.50E-08	3.96E-09	Low	Medium
EHMC	5.8	8.48E-06	1.46E-06	Low	High
OC	7.35	3.00E-09	4.08E-10	Low	High

Table 5.4 Probability of Rapid Biodegradation

	Linear (BW1)	NonLinear (BW2)	Ultimate (BW3)	Primary (BW4)	MITI Linear (BW5)	MITI NonLinear (BW6)	Prediction
PABA	0.6254	0.8287	2.849	3.5492	0.5563	0.566	**YES**
BP3	1.0215	0.9862	2.6926	3.6179	0.4764	0.3921	**NO**
EHMC	1.0238	0.9991	2.9378	4.0039	0.63	0.6352	**YES**
OC	1.4212	1.0000	2.8000	3.7600	0.3315	0.1254	**NO**

5.2.2 ISFs and greywater

The same six intermittent sand filters as in Chapter 3, prepared with different configurations regarding depth, media size and layers (Table 5.2) and operated for 8 months, were used for this experiment. As previously explained, all the ISFs were equipped with a geotextile filter pre-treatment (polypropylene nonwoven needle-punched fibers; pore size 0.14 mm) above the sand surface to remove suspended solids from raw GW influent.

Table 5.5

Configuration of ISFs Sand Media Layers and Nominal Particle Size (d_{10})

<table>
<tr><th></th><th colspan="6">ISF Column</th></tr>
<tr><th>Depth</th><th>A</th><th>B</th><th>C</th><th>D</th><th>E</th><th>F</th></tr>
<tr><td>0-20 cm</td><td>0.60 mm</td><td rowspan="2">0.60 mm</td><td>0.60 mm</td><td>0.90 mm</td><td>0.90 mm</td><td rowspan="3">0.60 mm</td></tr>
<tr><td>20-40 cm</td><td></td><td>0.30 mm</td><td>0.60 mm</td><td>0.60 mm</td></tr>
<tr><td>40-60 cm</td><td></td><td></td><td></td><td></td><td>0.30 mm</td></tr>
</table>

The influent greywater consisted of a 40:60 mixture of laundry and shower effluents collected from a single person daily use of a selected set of personal care products. Hydraulic loading rate was a daily 16 ml/cm2 split into three equal discharges (9 AM, 1 PM and 6 PM).

Parameters (TSS, COD, TP, TN) were measured following standard methods and the reduction rates were observed to evaluate biological activity. UV Filters were determined by solid phase extraction and liquid chromatography coupled with a mass spectrometer (Bratkovics et al., 2011). UV filter compounds were all spiked directly from >99% purity products supplied by chemical companies for a target concentration of 1 mg/L in the LLGW. Sampling was performed during the first three and last two months of operation, to evaluate the change in removal rate.

Table 5.6
LC-MS Detection characteristics

	LOD (mg/L)	Std Curve R^2 (0.05 to 0.3 mg/L)	LOQ - Conc 20 times (mg/L)	Recovery rate
PABA	0.05	0.9972	0.0025	104.85%
BP3	0.01	0.9975	0.0005	101.61%
EHMC	0.01	0.9985	0.0005	64.88%
OC	0.05	0.9946	0.0025	77.29%

5.3 RESULTS

5.3.1 Change of form of UV compounds in water and greywater

The first evaluation was the recovery rate and change of form of the UV compounds in water and greywater. Only PABA was recovered in concentrations similar to the expected, the other three compounds were measured in lower concentrations, which resemble the theoretical maximum dissolved concentration according to the USEPA EPISuite 2011. This means that a part of the spiked compounds probably adsorpted to particles in greywater or precipitated in the water matrix and was most likely removed by simple filtration. This mechanism has an important role in the removal of UV compounds.

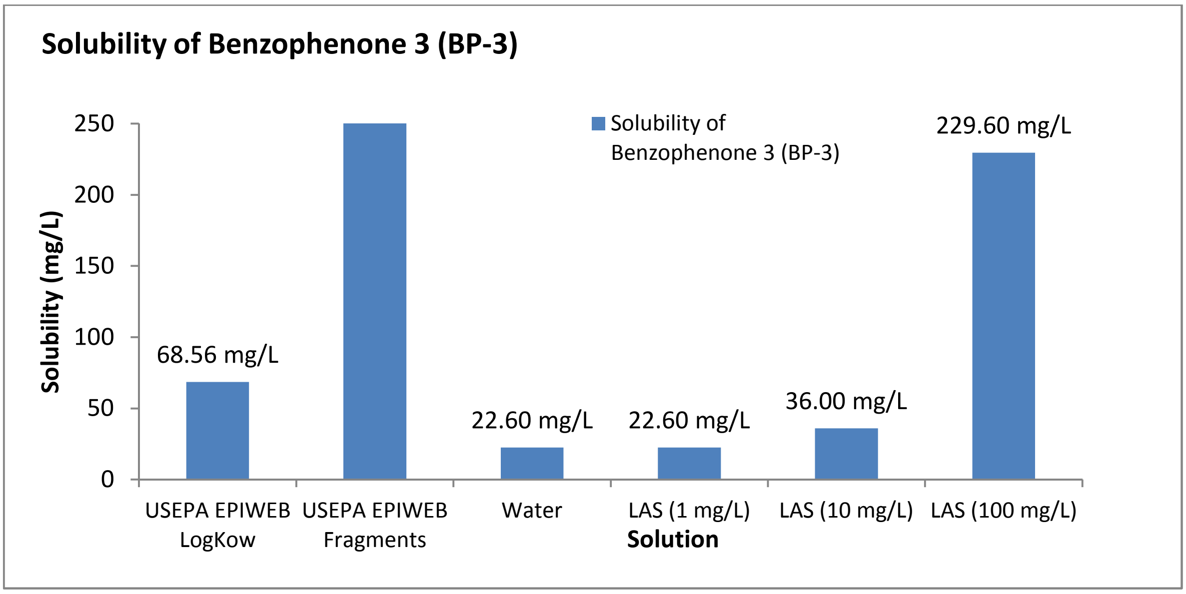

Figure 5.1 Change in solubility of Benzophenone

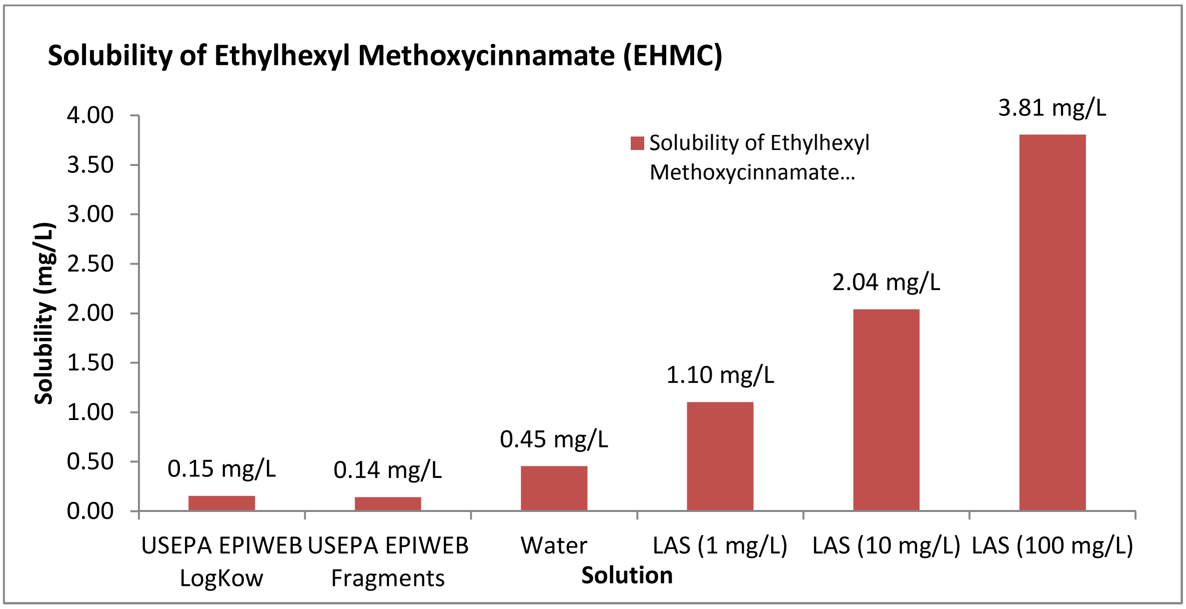

Figure 5.2 Change in solubility of Ethylhexyl Methoxycinnamate

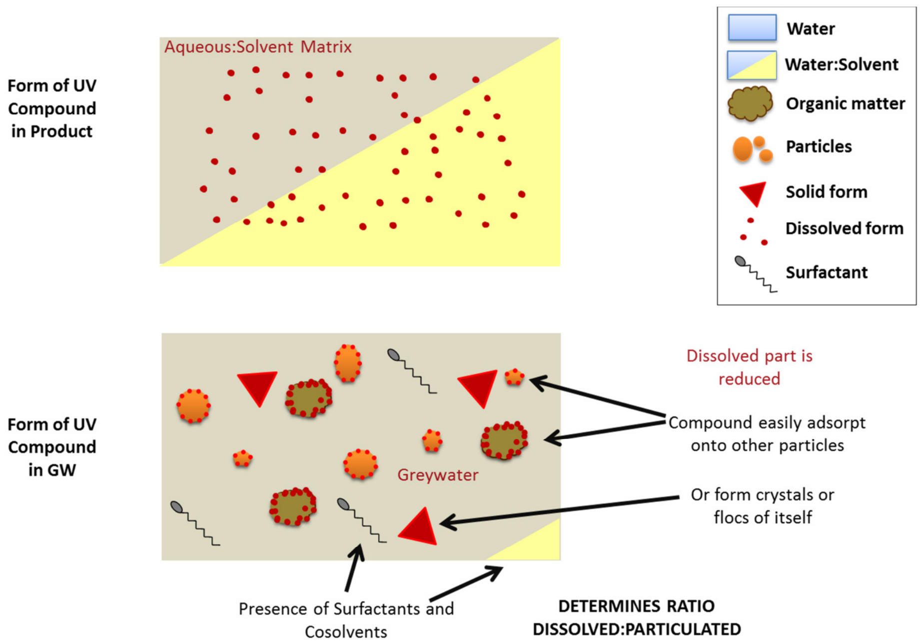

Figure 5.3 Possible mechanism of UV form in greywater

5.3.2 Removal of UV Compounds from greywater by ISFs

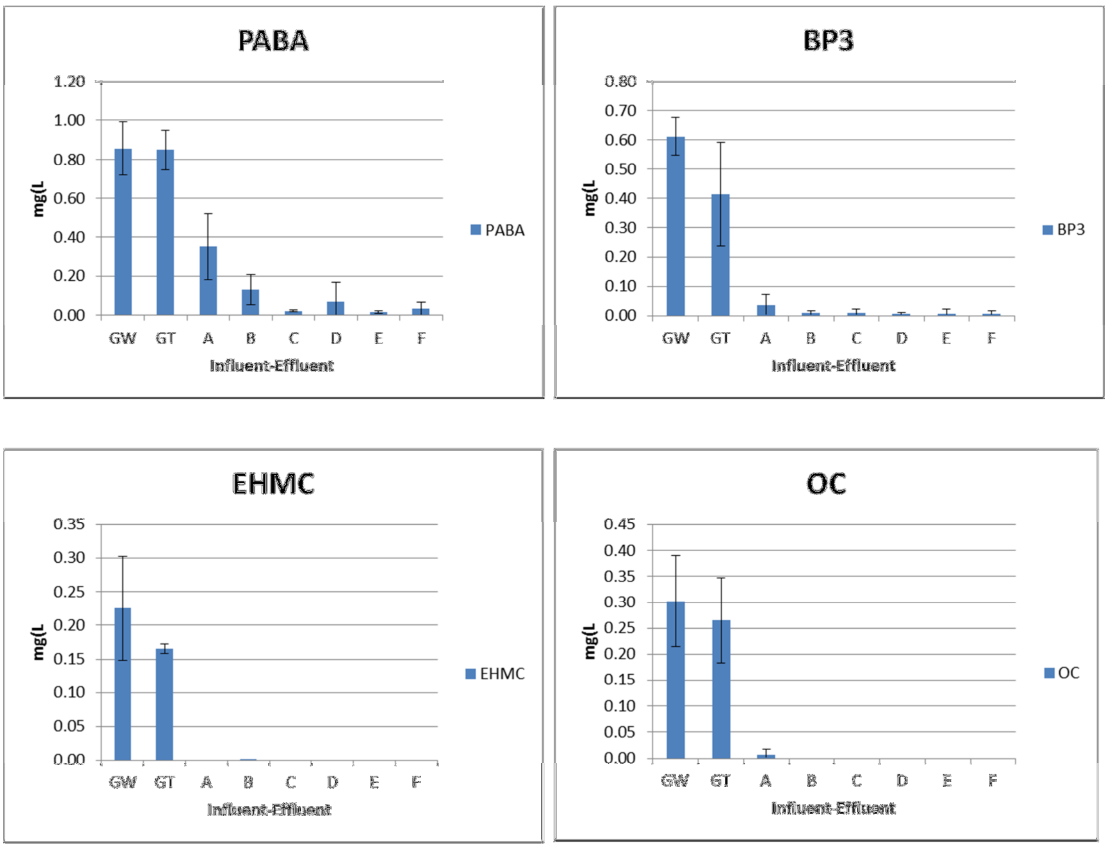

Figure 5.4 Removal of UV Compounds by ISFs

Regarding the removal of the dissolved part of the hydrophobic compounds, the concentration reduced above 91% even in the shallowest ISF-A (20 cm), whereas the removal of the hydrophilic one (PABA) was noticed to improve with the increase of depth. Probably the major mechanism is the attachment of the hydrophobic compounds to the sand surface; however, the biodegradation and final fate of these compounds in the sand as well as the interactions with surfactants, which affect the solubility rate, are still unclear.

In conclusion, ISFs showed a very good performance in removing these compounds under the limit of quantification in this experiment (0.0005 ppm concentration - 99.95% removal).

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Chapter 6

COST AND BENEFITS OF INTERMITTENT SAND FILTER FOR RECLAMATION OF GREYWATER AND REUSE IN IRRIGATION

6.1 INTRODUCTION

To evaluate the viability of implementing a treatment system for greywater and reusing the effluent in irrigation, both costs and benefits must be evaluated. The cost of implementing a system is highly variable depending on the local economy, the availability of materials, the quality of the materials and others. Furthermore, the costs of periodical maintenance work should be included. The failure of the system, which largely depends on the hydraulic loading rate, will influence the frequency of such maintenance, and therefore a comparison between the quality of produced effluent, the area required and the regularity of maintenance must be done. At the same time, the area possible to be covered will produced a benefit in terms of crop harvested.

6.2 METHODOLOGY

A single-family scenario was used for the feasibility analysis. It was assumed that enough land was available for small family farm, and that no additional work was required for the greywater to reach by gravity the treatment system.

The potential crops for each area will depend on the type of weather. Several crops that require irrigation and are common in Guatemalan rural area were used for estimation.

It was assumed that the users could not incur in the costs for installation of the treatment system, and therefore a financial aid is needed. As much as the systems are considered "low-cost", many of the inhabitants in the target areas live with less than $1 per day (extreme poverty), and although the costs can be recovered on the long run, it is the startup stage that seems unfeasible.

Microcredit financing is a form of loan services provided by microfinance institutions (MFIs). MFIs are financial providers that focus, often exclusively, on delivery of financial services targeted at low-income clients whose incomes sources are typically informal, rather than wages from registered employers (Rosenberg et al., 2013). These institutions provide small capital loans for large number of creditors. However, the interest rate is generally high, due to the large numbers of small loans managed.

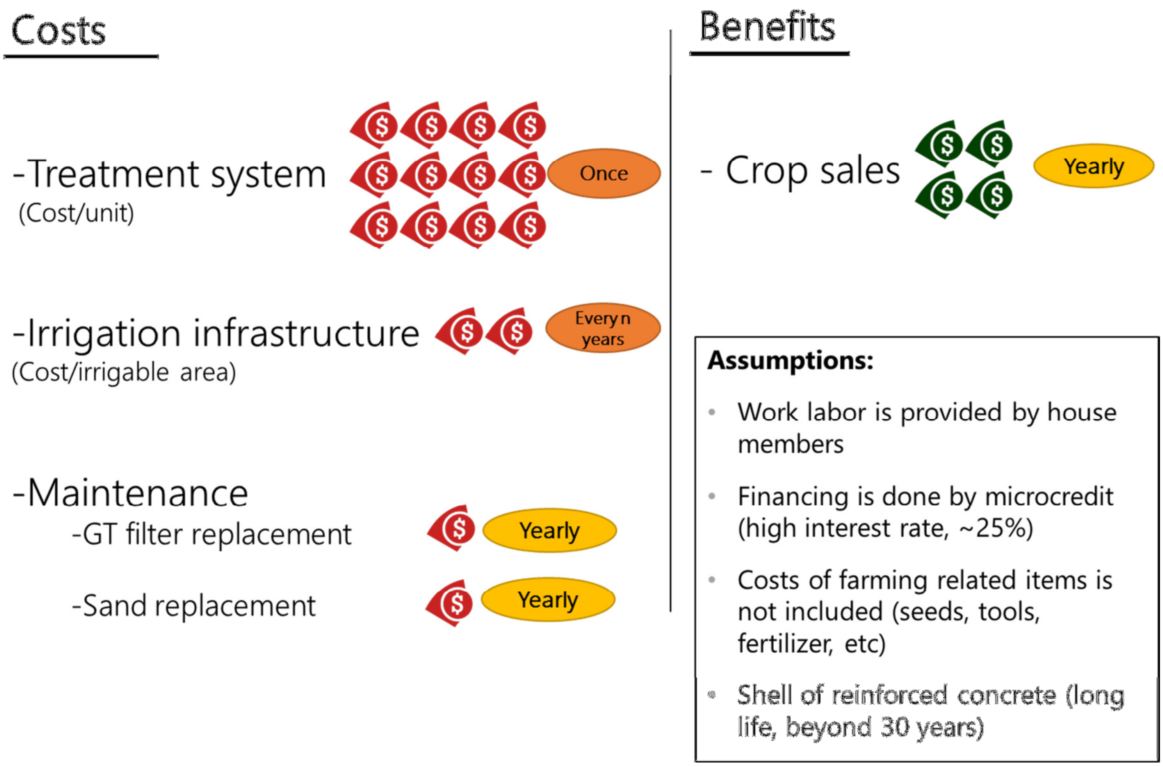
Example Scenario

Assumption

1 family = 5 members
100 L / person
80% is greywater

400 L available daily → HLR = 16 cm d^{-1}

Area required: 2.5 m^2
Media depth: 0.60 m
Assuming all construction work is performed by family

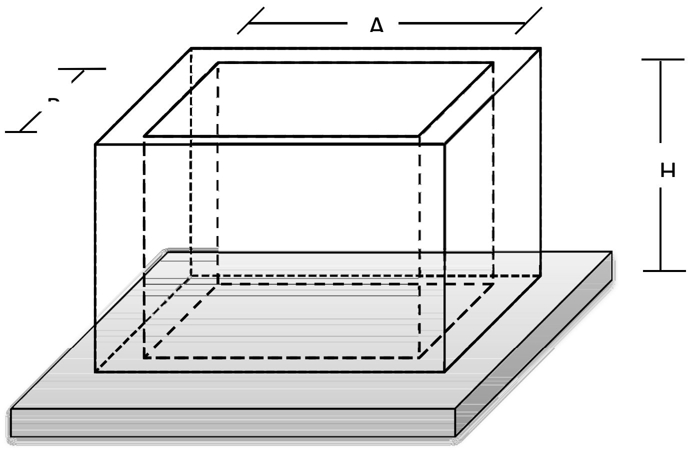


For the estimation of costs, a guide of prices provided by SEGEPLAN (Office of Planning from Guatemalan Government) was used (SEGEPLAN, 2013). The prices are provided in Guatemalan Quetzal (GTQ, Q). In this analysis, all prices were converted to US Dollars (USD, $) at an exchange rate of 1 USD = 7.63 GTQ.

6.2.1 Treatment system costs

6.2.1.1 Treatment system

Generally, installation costs include the costs of raw materials, tools and hand labor, plus works regarding the arrangement of the location (digging, leveling, etc). The assumed design of the ISF is that of a rectangular shell made of reinforced concrete. The thickness of concrete, size of steel rebar and other parameters of the shell were designed assuming the walls of the shell acting in cantilever supporting the pressure exerted by the sand inside the shell.



Foundation thickness	10cm
Wall thickness	10cm
A (inner)	160cm
B (inner)	160cm
H (inner)	70cm
Media h	60cm

Figure 6.1 Square shell for ISF

Based on the assumed pre-dimensioned shell, as in the Figure above, the necessary materials are as follows:

Table 6.1 Materials and cost of ISF shell

Concrete	Quantity		Unit Cost	Total
Portland cement	8.00	sacks	$ 10.35	$ 82.83
Thick aggregate	0.54	m^3	$ 22.94	$ 12.29
Sand	0.54	m^3	$ 16.38	$ 8.78
Structural steel #4	5.03	qq	$ 70.77	$ 355.96
Steel coil	4	pound	$ 1.00	$ 4.00
Wood	2	m^2	$ 58.98	$ 117.96
Sand Media	1.5	m^3	$ 16.38	$ 24.57
			TOTAL	**$ 606.40**

6.2.1.2 Sand replacement

The failure of ISFs will occur by clogging of the top layers of the system (5 to 10 cm depth from the surface). Generally, the biomass will accumulate depending on the intensity of the HLR. In this example, a HLR of 16 cm/d was assumed.

Although alternative methods exist for removing the accumulated organic matter, in this example sand replacement is assumed as the maintenance method. This method is considered to require simple skills, although it might be heavy work. It is also assumed that the users employ themselves in agricultural jobs; therefore, the maintenance tasks are not too difficult or unfamiliar for them to be done.

Method
Top layer replacement
How deep?
0-10 cm.
How often?
Approx. 3 times every 2 years.

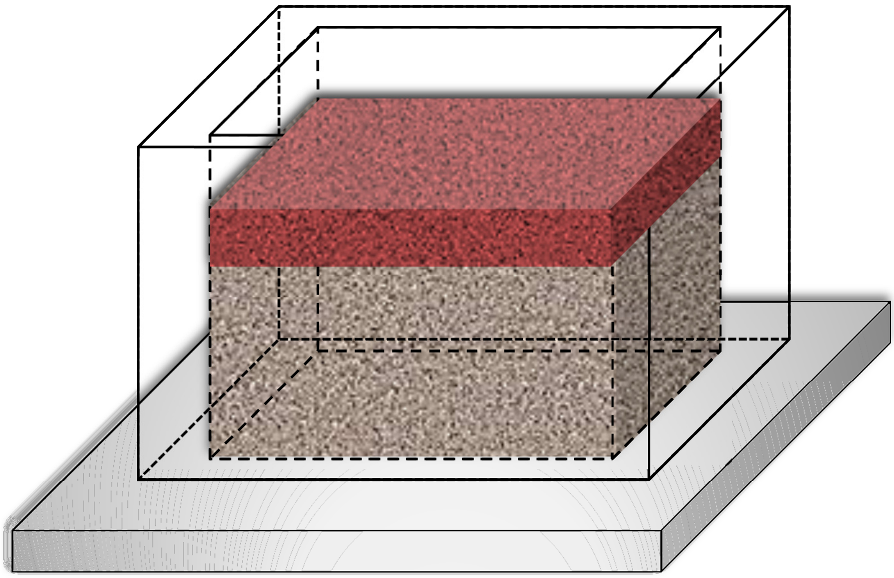


Figure 6.2 Top layer of sand to be replaced in maintenance

MATERIAL REQUIRED			**Cost**	
Area	2.5 m^2		Sand media	\$ 16.38 /m^3
Depth replaced	10 cm		Total	\$ 4.10 /1 time
Volume	**0.25 m^3**	**/1 time**		
			TOTAL	**\$ 6.14 Per year**
			(3 times every 2 years)	

6.2.1.3 Replacement of geotextile filter

Three different configurations were examined for the use of geotextile filter. Basically, the geotextile filter improved the lifetime when it was used in an upflow configuration, and even longer when a simple sponge was used as supporting material for the filter.

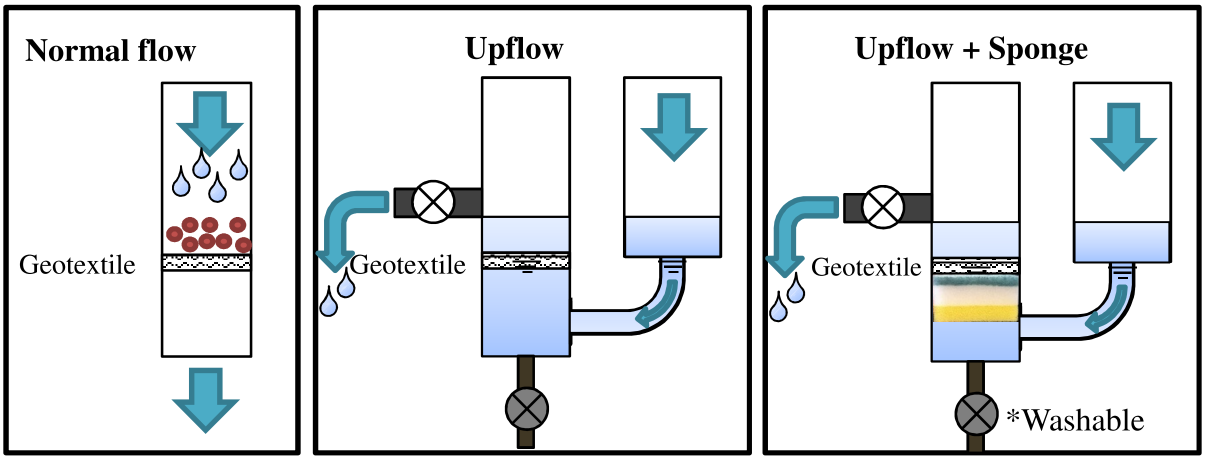


Figure 6.3 Configurations of geotextile filter in ISF system

The cost of geotextile per square meter is varied and generally provided including "handling and installation", but according to two local sources in Guatemala (Mayorga Garrido, 2012), the price of raw material in the range of 150 g m^{-2} is about $0.92.

Material Cost			
Geotextile	**$**	**0.92**	**/m²**
(Segeplan, 2013; Mayorga, 2012)			

Table 6.2 Cost of replacement of Geotextile in 1 year of ISF operation

	Normal	**Upflow**	**Upflow + Sponge**
Filter Capacity (m³/m²)	2.5	9.15	50.5
Volume/year	146 m³ *(400 L/day)*		
Required (m²/year)	58.40	15.96	2.89
Cost	**$ 122.89**	**$ 33.58**	**$ 6.08**

The use of simple sponges for support of material is also considered. During the experimental work, sponges proved to be easy to wash and recover to their original state. The price of sponge is about $ 0.1 per piece (200 cm^2), an assumed cost for a total of $7 per year for sponge and geotextile was assumed.

6.2.2 Benefits

The evaluation of benefits was made considering potential areas in Guatemala. Therefore, the analysis regarding crops, hydrological situation and others was made.

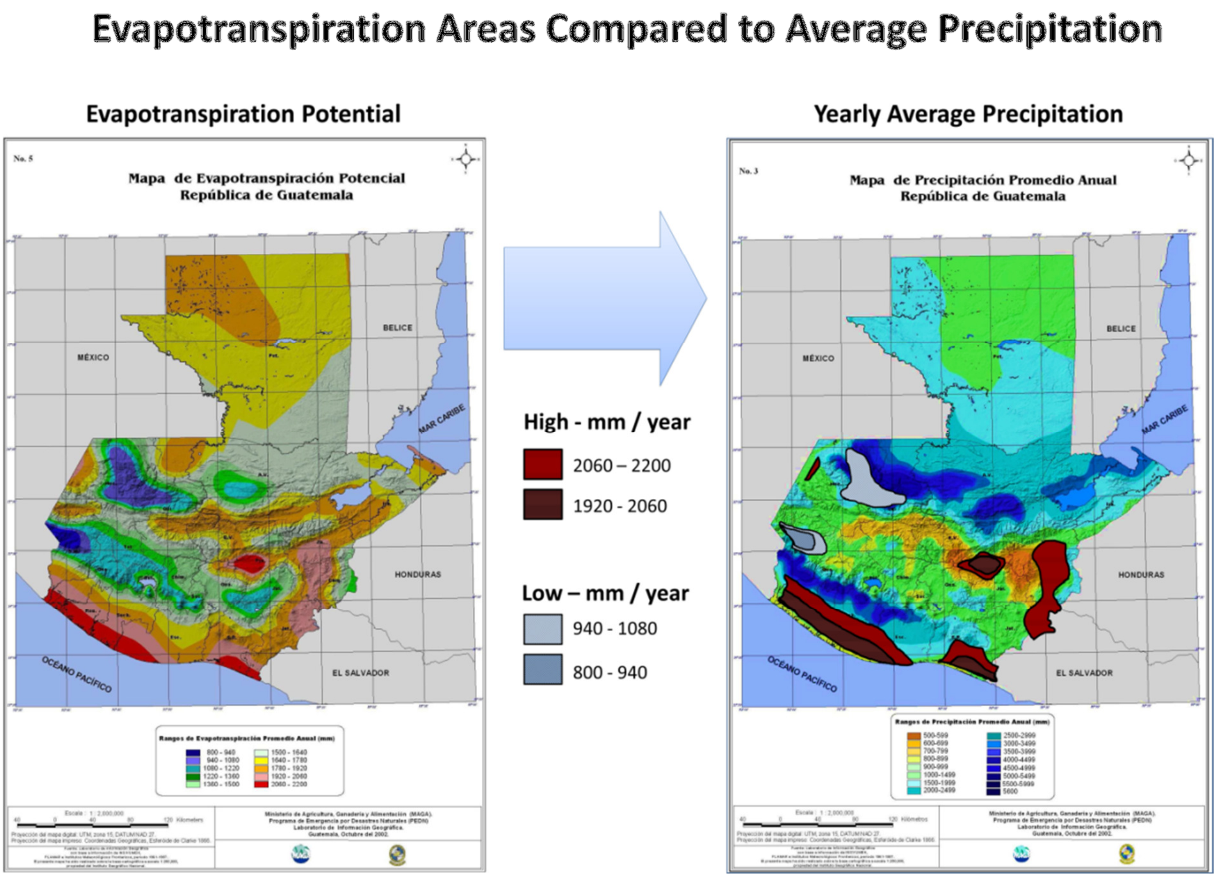


Figure 6.4 Evapotranspiration and precipitation in Guatemala

6.2.2.1 Benefits of irrigation

Table 6.3 Increase in the yield and income per hectare per year for different vegetables and fruits

		Not irrigated		Irrigated			
Crop	**Unit**	**Yield**	**USD**	**Yield**	**USD**	**Benefit**	**% difference**
Tomato	box	1714	$ 3,555.70	4286	$11,914.15	**$ 8,358.45**	**235%**
Green pepper	box	1428	$ 2,805.11	3570	$ 9,233.68	**$ 6,428.57**	**229%**
Cucumber	box	1428	$ 934.34	3570	$ 4,181.52	**$ 3,247.18**	**348%**
Watermelon	unit	7142	$ 1,310.22	17916	$ 4,458.98	**$ 3,148.75**	**240%**
Onion	quintal	428	$ 2,613.76	1070	$ 7,740.50	**$ 5,126.74**	**196%**
Lettuce	box	1714	$ 1,122.28	4286	$ 5,496.07	**$ 4,373.79**	**390%**
Sweet maize	quintal	250	$ 585.19	626	$ 2,355.05	**$ 1,769.86**	**302%**
Potato	quintal	457	$ 1,869.99	1142	$ 6,949.54	**$ 5,079.55**	**272%**
Carrot	dozen	17142	$ 3,744.17	42854	$11,343.91	**$ 7,599.74**	**203%**
Chile jalapeno	quintal	228	$ 737.75	570	$ 3,493.84	**$ 2,756.09**	**374%**
Cauliflower	bultos	2228	$ 1,311.27	5716	$ 5,221.76	**$ 3,910.48**	**298%**
Cabbage	bultos	1600	$ 805.11	4000	$ 2,944.43	**$ 2,139.32**	**266%**
Plantain	bultos	685	$ 1,044.30	856	$ 1,858.19	**$ 813.89**	**78%**
Avocado	ton	8	$ 3,224.12	10	$ 4,322.15	**$ 1,098.03**	**34%**
Lemon	ton	21	$ 3,695.94	26	$ 4,777.72	**$ 1,081.78**	**29%**

(MAGA, 2013)

Table 6.4 Labour generated per additional irrigated hectare per year

Workday generated (daily work and practices)	324 workdays per harvest 2 harvests per year	648 workdays
Fixed jobs generated	648 workdays/250 (constant) = 2.59 fixed jobs	2 fixed jobs
Direct beneficiaries *owner	Number of projects x 6 (average family members)	6 direct beneficiaries
Indirect beneficieries *employees	Fixed jobs x 6 (average family members)	12 indirect beneficiaries

(MAGA, 2013)

6.2.2.2 Determination of crop water requirement

The amount of area that can be irrigated with the effluent from the ISF, assuming a daily volume of 400 L, depends on the water requirement of the crops. For the crops in the previous table, the water requirement was calculated as follows:

Crop water requirement based on

$$ETc=Kc*ETo-P$$

ETc= Crop water requirement
Kc: crop constant
Eto: evapotranspiration
P: precipitation

Assuming the extreme scenarios (P=0)

Table 6.5 Crop Water requirements

	Crop constant			Water requirement (ETc)			
				Very high need	High need	Medium need	
				2200	1780	1220	*mm/y*
	Kc ini	Kc mid	Kc end	6.03	4.88	3.34	*mm/d*
Tomato		1.3225	0.7-0.9	7.97	6.45	4.42	
Green pepper		1.1025	0.9	6.65	5.38	3.69	
Cucumber	0.6	1	0.75	6.03	4.88	3.34	
Watermelon	0.4	1	0.75	6.03	4.88	3.34	
Onion		1.05	0.75	6.33	5.12	3.51	
Lettuce		1	0.95	6.03	4.88	3.34	
Sweet maize		1.15	1.05^12	6.93	5.61	3.84	
Potato		1.15	0.75^4	6.93	5.61	3.84	
Carrot		1.05	0.95	6.33	5.12	3.51	
Chile jalapeno		1.1025	0.9	6.65	5.38	3.69	
Cauliflower		1.05	0.95	6.33	5.12	3.51	
Cabbage		1.05	0.95	6.33	5.12	3.51	
Plantain*	0.5	1.1	1	6.63	5.36	3.68	
Avocado	0.6	0.85	0.75	5.12	4.15	2.84	
Lemon**	0.75	0.7	0.75	4.22	3.41	2.34	

*1st year
**70% canopy

6.2.2.3 Cost of irrigation per manzana

The cost of irrigation also depends on the area covered. Although it is difficult to downscale the real costs of irrigation systems, the conversion from available average costs per "manzana" for drip irrigation systems was made as follows:

Table 6.6 Cost of irrigation

	Cost/manzana		Per m²
Vegetables	Q 18,000.00	$ 2,359.11	**$ 0.34**
Fruit trees	Q 15,000.00	$ 1,965.92	**$ 0.28**

1 manzana = 1.72 acre = 6961 m²

(SEGEPLAN, 2013)

Finally, with the water requirement calculations, the irrigable area is possible to be estimated, dividing the 400 L d^{-1} by the required L m^{-2} d^{-1}, and the calculation of irrigation costs is made also for that area. The summary for this example is in the next table, considering three scenarios with different degrees of water requirement.

Finally, for the loan payback analysis, the crop with highest return was used (carrot).

Table 6.7 Irrigation Costs and Net Income from Irrigated Crops

	VERY HIGH NEED				HIGH NEED				MEDIUM NEED			
			Once*	Per year*			Once*	Per year*			Once*	Per year*
	L m^{-2} d^{-1}	Area (m^2)	Irrigation Cost	Net income	L m^{-2} d^{-1}	Area (m^2)	Irrigation Cost	Net income	L m^{-2} d^{-1}	Area (m^2)	Irrigation Cost	Net income
Tomato	7.97	50.18	$ 17.01	$ 59.79	6.45	62.02	$ 21.02	$ 73.89	4.42	90.49	$ 30.67	$ 107.81
Green pepper	6.65	60.19	$ 20.40	$ 55.58	5.38	74.40	$ 25.21	$ 68.70	3.69	108.55	$ 36.79	$ 100.23
Cucumber	6.03	66.36	$ 22.49	$ 27.75	4.88	82.02	$ 27.80	$ 34.30	3.34	119.67	$ 40.56	$ 50.04
Watermelon	6.03	66.36	$ 22.49	$ 29.59	4.88	82.02	$ 27.80	$ 36.57	3.34	119.67	$ 40.56	$ 53.36
Onion	6.33	63.20	$ 21.42	$ 48.92	5.12	78.12	$ 26.47	$ 60.47	3.51	113.97	$ 38.63	$ 88.22
Lettuce	6.03	66.36	$ 22.49	$ 36.47	4.88	82.02	$ 27.80	$ 45.08	3.34	119.67	$ 40.56	$ 65.77
Sweet maize	6.93	57.71	$ 19.56	$ 13.59	5.61	71.32	$ 24.17	$ 16.80	3.84	104.06	$ 35.27	$ 24.51
Potato	6.93	57.71	$ 19.56	$ 40.10	5.61	71.32	$ 24.17	$ 49.57	3.84	104.06	$ 35.27	$ 72.32
Carrot	6.33	63.20	$ 21.42	$ 71.70	5.12	78.12	$ 26.47	$ 88.61	3.51	113.97	$ 38.63	$ 129.29
Chile jalapeno	6.65	60.19	$ 20.40	$ 21.03	5.38	74.40	$ 25.21	$ 25.99	3.69	108.55	$ 36.79	$ 37.92
Cauliflower	6.33	63.20	$ 21.42	$ 33.00	5.12	78.12	$ 26.47	$ 40.79	3.51	113.97	$ 38.63	$ 59.51
Cabbage	6.33	63.20	$ 21.42	$ 18.61	5.12	78.12	$ 26.47	$ 23.00	3.51	113.97	$ 38.63	$ 33.56
Plantain*	6.63	60.33	$ 20.45	$ 11.21	5.36	74.57	$ 25.27	$ 13.86	3.68	108.79	$ 36.87	$ 20.22
Avocado	5.12	78.07	$ 26.46	$ 33.75	4.15	96.50	$ 32.70	$ 41.71	2.84	140.79	$ 47.71	$ 60.85
Lemon**	4.22	94.81	$ 26.77	$ 45.30	3.41	117.17	$ 33.09	$ 55.98	2.34	170.96	$ 48.28	$ 81.68

Summary for Estimation of Microcredit Loan and Return

Scenarios:
- Interest – 25% per year
- Payable timespan – 5 to 10 years
- Subsidizing of initial payment – 0, 25, 50, 75%

Calculation of amortization by Loan Calculator (BankRate)

Expense

Initial
- System: $606 $610
- Irrigation: $38.29 $40

$650

Yearly
- Maintenance:

Geotextile: $6.08 $7

Sand: $6.14 $7

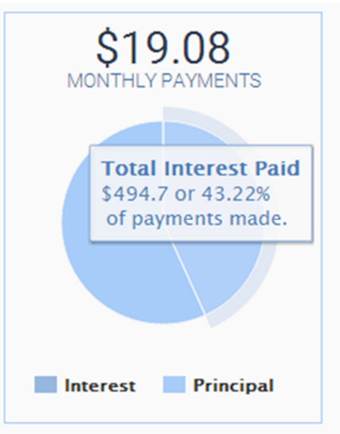
$14 / year

Benefits

Yearly
- Crop production

Carrot $129.29 $130 /year

Scenario: 5 years, Subsidy 0%



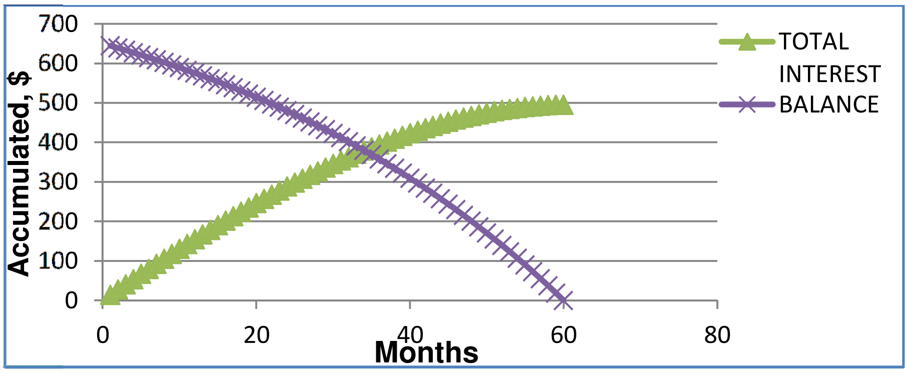


Figure 6.5 Capital payment vs Interest

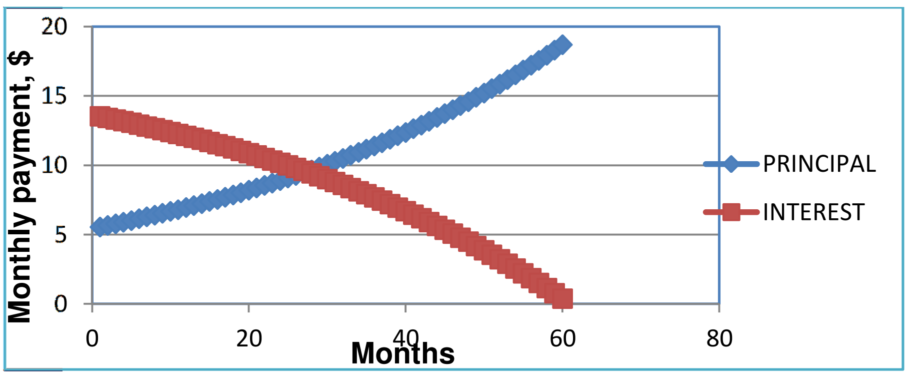
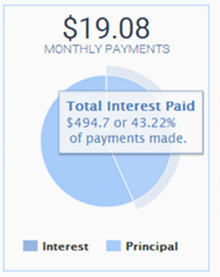


Figure 6.6 Composition of Monthly Payment (Principal + Interest)

Assuming a timespan for payback in 5 years

$650 - 5 years
Subsidy 0%

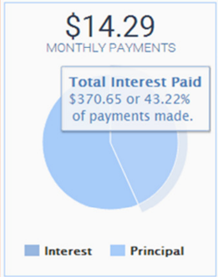


Per year - $228.96
+ $14

Total per year
$ 242.14

Net Balance
- $ 112.14

$487 - 5 years
Subsidy 25%

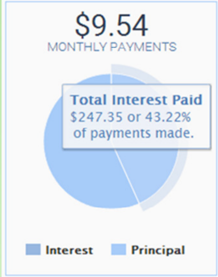


Per year - $171.48
+ $14

$ 185.48

- $ 55.48

$325 - 5 years
Subsidy 50%

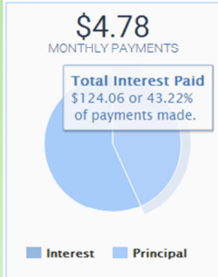


Per year - $114.48
+ $14

$ 128.48

$ 1.52

$163 - 5 years
Subsidy 75%



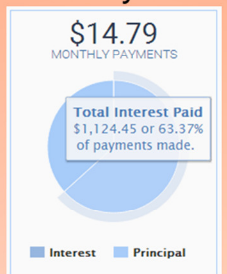
Per year - $57.36
+ $14

$ 71.36

$ 58.64

Assuming a timespan for payback in 10 years

$650 - 10 years
Subsidy 0%

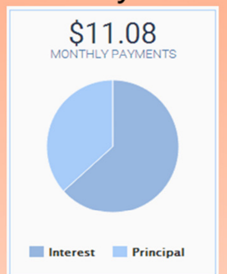


Per year - $177.48
+ $14

Total per year
$ 191.48

Balance
- $ 61.48

$487 - 10 years
Subsidy 25%



Per year - $132.96
+ $14

$ 146.96

- $ 16.96

The results of the estimation indicate that subsidy from 50% and above is necessary for a payback of 5 years or less. And this is assuming the most profitable scenario in the example calculated. However, several calculations were done on extreme cases. The yield of small farms worked intensively can be higher, and the incidence of precipitation can also improve the production in some areas.

Another thing to be considered, regarding the profits, is to have a planned crop selection, based on market requirements to avoid overproduction of single crops and lowering prices.

The interest rate of 25% is common for small credits, but if a project is managed by governmental institutions in collaboration with financiers, it may be possible to lower them as well. However, if we consider examples of countries like Japan, where for the decentralized sanitation the Government will cover 90% of initial costs, it should be quite feasible and sustainable.

6.3 CONCLUSIONS

- Cost of installation can be significantly higher than the yearly benefits (5 to 10 times). However, construction in series could reduce costs.
- The estimated benefits from crops are for large scale croplands (which are less efficient). Small scale farming could increase the productivity and benefits.
- Subsidizing the installation costs is highly advisable for successful implementation of ISFs. (Existing programs as PAFFEC 2015).
- Alternatively, different type of materials for the construction of the treatment system should also be considered.

6.4 REFERENCES

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Chapter 7

CONCLUSIONS

The use of intermittent sand filter bioreactors for reclaiming domestic greywater for its reuse in agriculture was investigated. A mixture of laundry, shower and washbasin greywater was used. Kitchen sink greywater was excluded based on previous researches that indicate its detrimental effects in terms of pathogen regrowth.

The main goals of this research were: to evaluate an improved ISF system by implementing a geotextile filter pretreatment to reduce the load of SS to the bioreactor and control de type of particles loaded; to evaluate the effects of physical parameters (media, depth, layering) and hydraulic loading rate (i.e. surface area) of a ISF bioreactor in the quality of effluent; and to evaluate the potential benefit of installing this systems in a real case scenario, comparing the installation and maintenance costs vs the benefits of crops produced.

It was found that geotextiles were be able to remove more than 50% of SS in greywater. Moreover, the removal of specific particles goes below the theoretical AOS. Reduction of large particles by pretreatment not only reduces the amount of accumulated particles but showed the potential to remove COD up to 30%. The materials with one side thermal-bonded as well as higher density showed best performance. The materials were able to filter an overall maximum of 200 to 250 cm of greywater before failure in the continuous use, and only 112 to 160 cm in the intermittent setup, meaning that if used in the same area ratio to the ISFs surface, a large amount of geotextile is needed to be replaced often. Using geotextile filter as pretreatment did not affect significantly the overall quality of ISFs effluent and positively reduced the accumulated volatile solids in the top layers of the media, effectively avoiding early clogging in fine media and decrease of permeability in medium sand during the experimental period. The use of geotextile filter may have potential for extending the initial lifetime of ISFs. The downside is the periodical maintenance and the material expense needed every 7 to 10 days in the current usage form. Using the geotextile in alternative ways showed to improve its lifetime from 10 to 30 fold.

Pretreatment of domestic greywater by geotextile filters ensured a performance of at least 8 months without backwash or any maintenance to ISFs with medium or coarse media in the top layer at the hydraulic discharge of 16 cm d^{-1}. Most of the treatment occurs in the top 20 cm layer, however, by increasing the depth of an ISF the removal of SS and dissolved organic matter can be improved to levels that could reduce the risk to the performance of irrigation systems. Layering with uniformly graded coarser media (d_{10}=0.9 mm) in top did not significantly affect the lifetime of ISFs or the quality of effluent. Layering with fine media (d_{10}=0.3 mm) in bottom improved the removal of dissolved organic matter, suspended solids and E. Coli.

Concentration of LAS is below 3.55 mg L^{-1} at depths of just 20 cm (91.8%). Implementation of a polishing layer of fine sand reduces the concentration to less than 1 mg L^{-1}, 97.9% of total load. Removal of E. Coli was below the required level for intensive handling use of effluent. However, several measures can be used to avoid health issues. Generally, the ISFs performed with a potential enough to treat relative large volumes (160 L m^{-2} d^{-1}) of greywater to high quality levels in terms of organic and suspended contents that would allow the implementation of high-efficiency irrigation systems and therefore improved production capacity.

Increasing of the hydraulic daily discharge (i.e. reduction of surface area) reduced the lifetime of ISFs and marginally reduced the quality of effluent in terms of SS and dissolved organic matter. Although higher SS was observed, it was mostly non-settleable particles, and therefore less likely to cause immediate damage to irrigation systems. In contrast, the total filtering capacity of the systems was higher when greater daily discharges were used. Low removal of E. Coli was observed a maximum of 2 log units under the experimental conditions (8 cm d-1), so additional measures must be considered for safe reuse of LLGW treated by ISF.

ISFs showed a very good performance in removing hydrophobic UV compounds under the limit of quantification in the experiment (0.0005 ppm concentration - 99.95% removal), a low level even for trace concentrations. However, for hydrophilic compounds, the removal rate was similar to that of dissolved organic matter.

The implementation of ISFs in a rural scenario showed the potential to create income directly and indirectly, through production and labour. However, the benefits will generally depend on whether the place is under high need of irrigation or not, and the possibility of being subsidized by government.