Optimization of On-site Treatment Systems:

Filtration Using Geo-textile Filters for Source Separated Black Wastewater

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MSc in Sustainable Water & Sanitation, Health & Development

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Summary

Decentralized onsite treatment systems are widely applicable and prized in sparsely and remotely located settlements. Those systems are appreciated for environmentally sound approaches, socio-economic and physical barriers. However, recurrent media clogging, ponding, saturation, space requirements and incurred operational and maintenance costs pose criticism on those systems.

The study was carried out on the fundamental bases that most of the pollutants in wastewater exist on particulate or colloidal form or are transformed to other form in the process. This by removing those particulate matters at the early pretreatment step, much could be gained on the consecutive treatment steps.

Filtration performance of three different non-woven geo-textiles (i.e. polypropylene and jute wool) to highly concentrated source separated black wastewater influent was evaluated in laboratory scale, aiming to optimize treatment process as pretreatments. Experimental test was established into two phases both in Column and FilterBox for over five months in the column experiment and a month and half in the FilterBox experiment. Experiments were also subjected to variable resting and drying events.

Fresh samples were collected and analyzed d according to the standard methods for examination of water and wastewater (21th edition) and HACH LANGE chemicals. Data analysis was subjected to Minitab16 and Excel office 2010. Results are mainly summarized with boxplots and trend analysis of filter performance over time.

The textiles showed similar median removal potential of about 55% -65% for COD, 35-45% for TS, 60-70% for TSS, 50-65% for TVS and around 20-25% for Tp in both experiments. An average removal of 41.5%, 38.9% and 41.16% in textile1, 2 and 3 was measure for BOD5 on the FilterBox experiment. Removal potential to orthophosphate was minimal, in some cases even increased in concentration in the effluent compared to the inlet.

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CHAPTER 1

General Introduction

1.1. Background:

Everyday about two million tons of sewage is discharged to the world's waterways, and this affects an estimated 245,000km^2 marine ecosystems where many livelihood depend on for living (UNEP 2010). Moreover, about 780 million and 2.5 billion people worldwide lacked access to safe drinking water and adequate sanitation facilities, respectively (WHO/UNICEF 2012). Ironically, it is projected that the 2015 millennium development goals (MDG), target for sanitation is not likely to be attained and there will be 2.4 billion people without access to improved sanitation facilities by the end. Though access to drinking water is on the track there will be about 605 million people without access to improved drinking water sources by the end of 2015. Those sanitation-induced problems coupled with other global environmental challenges are leading to disturbing health and ecosystem imbalances (Cheremisinoff 2002). An important share of the total burden of disease worldwide, around 10%, could be possibly prevented by improvements related to drinking-water, sanitation, hygiene and water resource management (WHO/UNICEF 2012).

It is obvious that addressing such sanitation problems will not be easy using the centralized treatment systems. The problem is millions of people are living in costal (UNEP 2010), inaccessible and ecologically sensitive areas those are not feasible for large-scale treatment facilities. Besides physical-environment and socio-economic constraints oppose connecting a few households to central treatment facilities (Siegrist, Tyler et al. 2000; Heistad, Paruch et al. 2006; Jenssen, Krogstad et al. 2010). Therefore, looking for variety of solutions depending on the vital socio-economic and environmental bases is evident.

In response to that, the evolving low-cost decentralized sanitation and onsite based small-scale treatment treatments with reuse potentials will have to play a major role (Roeleveld, Elmitwalli et al. 2006). One of these is a source-separate based decentralized approach. The ideology is that wastewater streams can be segregated at source according to their degree and type of pollutants for efficient handling and reuse potentials before further treatment processes. There are a couple of advantages with this approach. These include resources reuse (bio-energy, nutrient and water), volume reduction, low cost as portion of the wastewater (grey water) need less treatment degrees due to low pollutant concentrations (Roeleveld, Elmitwalli et al. 2006; Meinzinger and Oldenburg 2009a).

Onsite wastewater treatment systems (OWTS) can be generally categorized into soil infiltration systems, package treatment plants, and constructed wetlands (CWs) (Heistad, Seidu et al. 2009b). Here after in this work, when referred as onsite treatment, it is meant to these categories and to their corresponding common filter media (e.g. soil, shell-sand and Filtralite® P). Despite the wider applications and adaptability of OWTS two conflicting concepts have emerged about their long-term performances. One concept is that of a long-term acceptance rate which allows the systems to function at its preferential design. The other concept is that of progressive decline or "failure" that assumes the capacity of a media continues to decrease. Hence, their sustainable functionality is highly influenced by the wastewater constituents applied (Levinel, Tchobanoglous et al. 1991; Adam, Krogstad et al. 2005; Jenssen, Krogstad et al. 2010; Murat Hocaoglu, Insel et al. 2010) beside the media property, loading and application patterns (Jenssen and Siegrist 1990). As a result, systems are subjected to recurrent clogging, ponding (Winter and Goetz 2003; Zhao, Zhu et al. 2009), saturation (Adam, Søvik et al. 2007b) and periodic filter shifting that lead to extra operational and maintenance (O&M) costs (Jenssen, Krogstad et al. 2010) or might fail to meet effluent discharge limits. This is because OWTS treatment quality depends on the ability of the media to absorb and purify the applied wastewater (Jenssen and Siegrist 1990; Jenssen, Maehlum et al. 1993).

Thus, accumulation of wastewater constituents in the pore media is regarded as the factor causing clogging and is one of the worst operational problems once it occurs on the surface, 0-15cm (Zhao, Zhu et al. 2009) and (Knowles, Dotro et al. 2011). It leads to anaerobic conditions of the system and then further reduces the pollutants removal efficiency and infiltration rate of the media (Jenssen, Maehlum et al. 2005; Zhao, Zhu et al. 2009) and thereof the whole system functionality.

Therefore, optimization those constraints by reducing the inlet wastewater concentrations prior to onsite treatment technologies could basically enhance their wider applications and sustainability. This is the prime interest of this study.

1.2. Problem Statement

Generally, on OWTS there are various factors interfering and acting simultaneously, which influence their proper functionality. For example, soil infiltration-based systems, beyond the applied wastewater concentrations; they are also subjected to site-specific properties like, media properties (rocky, poor hydraulic conductivity), shallow ground water levels and available space. Moreover, they are not optimized for nutrient recycling because; P is mainly retained in the soil matrix unless the saturated media is used for soil amendment. On the other hand, package treatment plants are criticized for their recurrent operational and maintenance (O&M) costs, media clogging and vulnerability to variations in inflow and loading rates (Heistad, Seidu et al. 2009b; Jenssen, Krogstad et al. 2010).

Various studies show that there is a clear interdependency between the wastewater strength and its impact on treatability and thereof sustainability of the system. Based on these studies, the more concentrated inlet wastewater the more demanding to deal about it. For example, (Levine, Tchobanoglous et al. 1985; 1991) found that treatability efficiency are strongly correlated with contaminate size distribution. Siegrist, McCray et al. (2004) highlighted strong correlation between clogging and the cumulative mass density of total biochemical oxygen demand (BOD) and total suspended solids (TSS), (Winter and Goetz 2003) also explained the link between rate of media clogging with filterable content of the wastewater (TSS & COD) especially particles > 50µm can lead to media pore physical clogging and enhance bridging. Moreover (Zhao, Zhu et al. 2009) revealed a correlation between clogging rate to the wastewater particulate matter than to the dissolved constituents on his research using glucose (dissolved) and starch (particulate) matters. Similarly, (Adam, Krogstad et al. 2005; 2007a) indicate rate of media saturation to P sorption depends on the inlet concentration.

OWTS Service longevity - existing and future challenges

In the US, OWTS are commonly expected to have service life of 10 to 20 years or more (WERF 2007). In cold climate, Jenssen and Krogstad (2002) estimated to have 15years life for P removal using Filtralite® P as filter media, when the inlet concentration is kept as low as about $10 mgPl^{-1}$. Heistad, Paruch et al. (2006), on compact up flow designs expect for about five-year P saturation service time. However, Adam, Søvik et al. (2007ba) suggested that prior studies, especially for nutrient P treatments were over estimated. Thus, the shorter service times the more costly for O&M inputs in OWTS uses. The early estimated longer service time and costs are also questioned by recent studies for some of the following reasons:

(1) **Cost:** According to the recent study by (Jenssen, Krogstad et al. 2010) in the Nordic countries, the greater cost in CWs is the cost of filter bed sizes (40m^2) and high cost of the Filtralite® P (approx. 30% of the total cost) of the treatment plant.

(2) **Resizing and Operational challenges:** The study also suggest the possibility of reducing the size to more compacted filter beds (to <10m^3) without compromising the treatment efficiencies, but anticipates the potential increase in O&M costs as the Filtralite® P has to be change more frequently, for the reason of saturation and clogging difficulties.

(3) **Keeping lower inlet concentrations:** Due to the current change in people´s life style and advanced technologies that use less water for flushing (vacuum toilets) and source separation technologies, a highly concentrated influent is expected. Therefore, filter medium will obviously loaded with highly concentrated wastewater, as a result higher rate of clogging is evident and proper functionality of the system will be reduced (Winter and Goetz 2003; Adam, Krogstad et al. 2005; Palmquist and Hanaeus 2005), on the opposite side O&M costs will rise.

4. **Issue of waste recourses recovery:** Recovery is quite difficult or at least reduced because of biotransformation and incorporations into OWTS media matrixes, unless saturated media are used in agriculture. Therefore, efficient early pretreatment and recovery using some filters can provide the maximum use possible and reduce burdens in the consecutive steps.

OWTS Current status and challenges in Norway

In Norway, about 19% of households are not connected to sewer systems and out of those soil infiltration accounts 59% as main treatment ((Heistad 2008) in Berg 2007). Eggen (2011) also highlights about 111,000 soil based treatment systems existing in the country, with unknown status for the old ones. According to Heistad (2008), there is an overall reduction in OWTS status in Norway compared to the US. However, he highlights an increasing demand for more compact and small-sized systems while a decreasing one for the common sand-filter systems in particular. Thus, reduction in use could relate to various limiting factors of which some could be unsustainable efficiency to meet discharge limits, unavailable space and user's willingness to operate the systems.

On the other hand, 90% of the Norwegian soils are glacial till and labeled as problematic soil for onsite infiltration systems due to its hydraulic property (Jenssen 1986). While the Norwegian design guidelines for onsite applications demand prolonged soil infiltration (Heistad 2008), which makes applications of those systems more complicated and possibly pose a threat for future expansions unless a special design engineering are incorporated. Especially the topographic feature, people´s interest to stay close to nature in remote areas (e.g. summer houses, mountain lodges, etc) and an overall high ground water level makes soil based treatments systems difficult though OWTS are ideal to practice in such existing situations.

Fabric filtration as pretreatment - A part of the solution

Various researches suggest that a better reduction in wastewater constituents at the early stages can potentially reduce the overall burdens in the subsequent treatment steps (Levinel, Tchobanoglous et al. 1991; Metcalf & Eddy, Tchobanoglous et al. 2003; van Nieuwenhuijzen, van der Graaf et al. 2004; Zhao, Zhu et al. 2009).

Generally, $BOD_{5/7,\ 20}$ (i.e., the five or seven days at a temperature of 20°C) are the optimal condition for redox of organic matter in biological treatment systems (Haandel and Lubbe 2007). However, keeping the optimal temperature in cold climates is questionable. Therefore, more engineered pretreatment facilities are basically crucial to reduce the influent load concentration and sizes to the subsequent treatment steps as it affects directly the available oxygen, hydrolysis, biodegradation and clogging mineralization rates *(section 2.5.3 &2.5.4).*

Geotextile fabrics have been extensively in use as filters in drainage systems, especially in geotechnical engineering works like highways (Palmeira, Tatto et al. 2011) in membrane bioreactors, to separate the sludge from the liquid effluent (Zahid and El-Shafai 2011) and as direct filters followed septic tank pretreatment, in the form of non-woven fabrics (Roy et al. 1998). Those fabric filters are commonly used following some pretreatment steps (septic/sedimentation or less concentrated domestic waste) but rarely in use as direct influent pretreatment filters (DIF).

Only a small number of research activities into DIF, mainly with up-flow floating filters followed by chemical coagulants have been reported, e.g. (Nieuwenhuijzen, Graaf et al. 2001). Volk, Bell et al. (2000) have also noted that a very few studies focused on waste constituents removal prior to filtration and/or especially during the coagulation step has experimented. In this study a direct influent filtration test as a potential first treatment step using fabric filters was carried out aiming to reduce the filterable content of a highly concentrated source separated black wastewater from vacuum toilet sources.

1.3. Objectives of the study:

The main aim of this experimental study was to study the feasibility of using textile filters as pretreatment to optimize OWTS by reducing the filterable wastes in the influent that triggers clogging, saturation and ponding or system failures.

In achieving this, the following specific objectives have been outlined:

- Research literatures on the subject matter on how the filterable wastewater contents influence the overall OWTS performance and service longevity tradeoffs.
- Test the removal potentials of the three textile filters to source separated black wastewater. Mostly to parameters that impacts system clogging and physical pore plugging.
- Study the textiles property to sludge, clogging developments and filtration performances for prioritizing.
- To draw suggestion thereof,

1.4. Rationale of the study

Shall all the above objectives met, this work could have the following insights:

- ***Treatment optimization and sustainability:***

  There are estimates to enhance longevity of treatment service time by about 10 years with proper pretreatments (e.g. García, Rousseau et al. (2007))

- ***Maximum resources reuse:***

  Organic and inorganic wastes accumulated above the textile filters could be directly used as raw input for biogas production and then after or directly for soil amendment with caution to heavy metals and pathogens, before further biodegradations and incorporated into or adsorbed onto other media matrix.

- ***Possibilities for new treatment design configurations:***

  Rather than the commonly septic tank followed treatments, a possibility of textile filters as pretreatment configuration for easily recovery of wastewater particulates and resize the consecutive treatment steps is a probability. The reason is effluent concentrations coming to the septic tank or filter media will not only less concentrate but also in smaller sized particulates. Thus, highly enhanced biophysical degradation in the successive treatment steps implies higher rate of clog mineralization. Hence, smaller sized particles can degrade biochemically at rapid rate than larger particles (Levine, Tchobanoglous et al. 1985) and in a reduced surface area (Dimock and Morgenroth 2006). Look *section 5.1.1* for explanations.

1.5. The study and treatment approach

Fig1 illustrates the study approach and targets of this study. The source-separated wastewater at source with low flush vacuum toilets (JETS^{TM}) and the urine were accountable for the highly concentrated black water. The figure illustrates there is a holistic post treatment approach both to the produced sludge and filtrated wastewater fractions (Appendix1). However, this work was mainly focused on indenting potential pretreatment textile filters as highlighted with light-greenish color in (Fig1) blew.

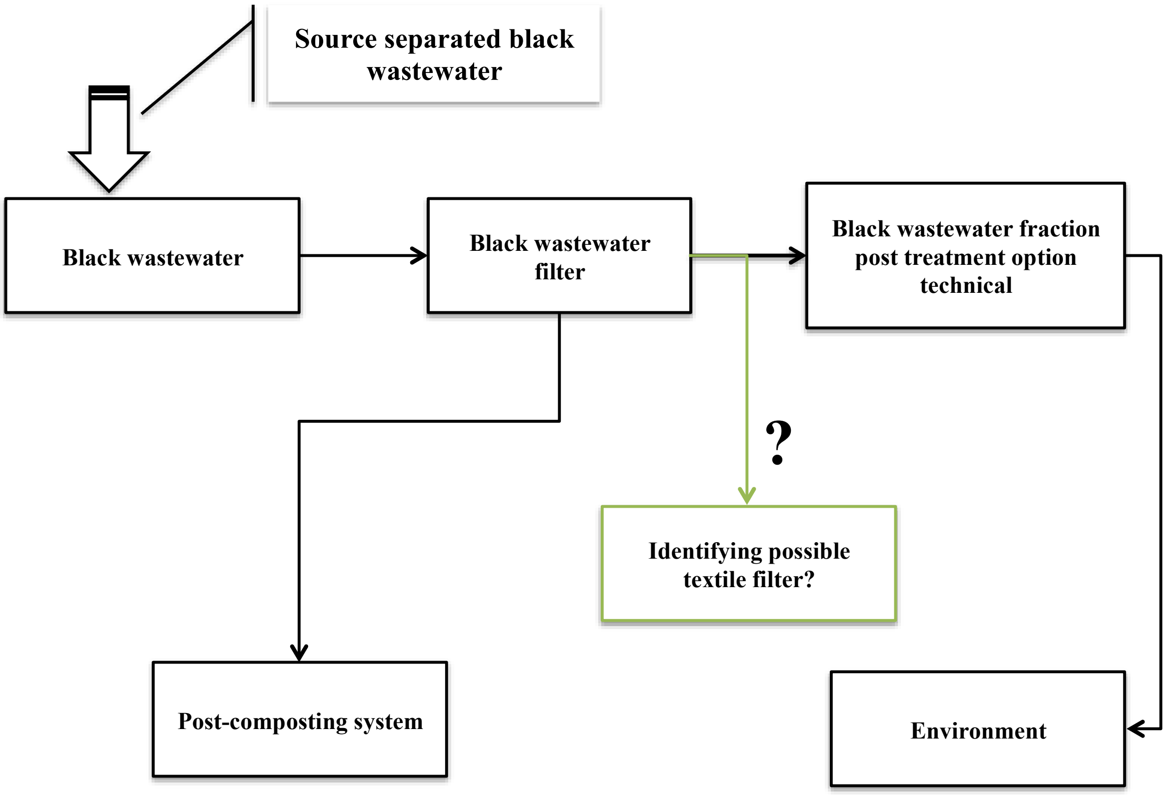


Figure 1. The study approach and focus.

Source: adopted from SanBox EU-research project (http://www.sanbox.info)

CHAPTER 2

Theoretical Framework

2.1. Introduction

This chapter deals with the theories and concepts underpinning this study. It starts with literature reviewing on the concepts of decentralized and onsite treatment technologies. It then focuses on source separation and black wastewater characterizations, media clogging challenges, impact of filterable content on clogging and treatment kinetics. Literature review on filtration mechanisms and fabric filter selection considerations were also discussed toward the end.

2.2. Onsite Treatment Systems

In principle, onsite wastewater treatment technologies are on the principles of mimicking the natural purification process. The soil, plants, microorganisms, temperature and all the environmental factors facilitate the treatment process. Historically, land applications are believed to be the first wastewater treatment to emerge. In the early 1900`s, some designs evolved to include raw wastewater pretreatments in septic tank followed by soil infiltration systems with some defined guidelines (Siegrist, Tyler et al. 2000).

The attitudinal shift towards OWTS was due to faded interest for central treatments as a result of financial constraints and a realization that such systems were not appropriate for all situations (Siegrist, Tyler et al. 2000). Their overall treatment performances can be viewed as optimal (Table2). Generally, the aim of wastewater treatment is protection of public health by enhancing hygiene, comfort, protection and conservation of water resources with possibility of resources recovery at affordable costs, in which onsite technologies are on the first queue on this regard.

Table 1. Common mechanisms of waste removal in OWTS

Constituent	**Common Removal Mechanisms**
Biodegradable organics	Bioconversions, microbial degradation and volatilization
Suspended and dissolved solids	Mechanical filtering, combination of physical straining and biological degradation
Phosphorus	Filtration, sedimentation, chemical binding, plant uptake
Nitrogen	Nitrification/denitrification, plant uptake, volatilization
Heavy metals	Adsorption to plants and debris surfaces, sedimentation
Pathogens	Natural die off and decay, physical entrapment, filtration, sedimentation, excretion of antibiotics from roots of plants

Sources: Crites and Tchobanoglous (1998), Knowles, Dotro et al. (2011)

Onsite treatments incorporate several physical, chemical and biological processes as summarized in (Table1). The major physical processes are settling of suspended particulate matters that are major cause of COD and TSS reduction. While the chemical processes involves adsorption, chelation and precipitation, which are responsible for the major removal of nutrients and heavy metals (Haandel and Lubbe 2007). In the biological processes, treatments are achieved mainly with the role of microorganisms as discussed in, *section 2.5.4*. Biofilm developments allow the degradation of organic matter, nitrification in aerobic zones and denitrification in anaerobic zones.

OWTS are diverse, so selection of the appropriate systems might depend on the nature and strengths of waste source, climatic factor, site condition and socio-economic bases. For example, in areas where soil infiltration is a constraint due to hydraulic or ground water level problems, use of mound systems might increase the filtration depth and residence time prior reaching the native soil. In contrast, a less concentrated source might use a sand filter or let the wastewater expose to the external environmental factors for natural treatment, like surface wetland might be preferred.

Table 2. Summary of OWTS and treatment potentials

System	**Organic BOD reduction**	**Ammonia reduction**	**Nitrate reduction**	**Phosphorus reduction**	**Pathogen reduction**
Constructed Wetland					
▪ Surface	+++	++	+	+	++
▪ Subsurface					
✓ HB	+++	++	+	+(+)	+
✓ VB	+++	++	+	+(++)	++
✓ Hybrid (VB+HB)	+++	+++	++	++(+++)	+++
Pond	+++	++	+	+	+++
Infiltration	+++	+++	+	+++	+++
Sand filter	+++	+++	+	++	+++
Mound system	+++	+++	++	+++	+++

Note: +++ (very high, > 90% removal), ++ (medium, 40-70% removal) and + (low, <40% removal). Sources: (Jenssen autumn 2011 lecturer summery), (Crites and Tchobanoglous 1998),

2.3. Decentralized vs Centralized Treatments

The notation centralized and decentralized treatment systems are rather vague and unclear. Some consider treatment systems that are connected with pipes and sewers to be as centralized treatment or “convectional”. However, these could be also a decentralized approach in a wider scale (e.g. a large-scale integrated constructed wetland in Beijing Olympic forest park with an area of 45,000m^2 (Xie, He et al. 2011)). This is because; others also define it from the perspective of size and service scale and the management approaches, (Fig2).

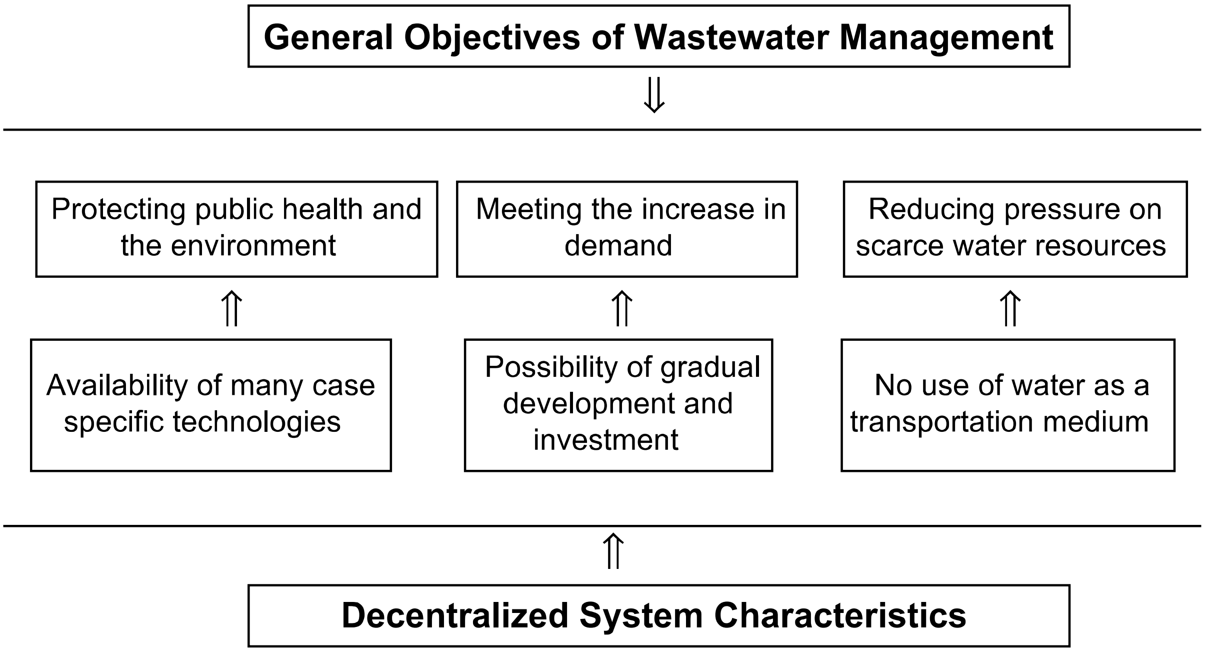


Figure 2. General objectives of wastewater treatment vs decentralized system characteristics.

Source: (Nam 2006)

While the decentralized approach is much of on individual sources treatment approach, i.e. treatment on sources where the waste is generated, but that could also be categorized as cluster, onsite, central and regional or even more based on the size and service scale. Generally, as the size and scale of function getting bigger the tendency to become a more of central treatment is visible. Nevertheless, one can see the immense advantages of small-scale onsite treatment facilities over conventional treatment approaches:

Application, Cost and Involvement

Onsite approaches can be easily adapt to limiting environmental factors (i.e. space, landscape, accessibility, soil and ground water factors) with reduced operational costs. Systems might have also higher probability to involve end users in keeping their systems functional and can indirectly create environmentally aware and involve non-professional communities. Treatment installation might as well use locally available inputs and reduce costs of transport and access difficulties.

Reliability, Vulnerability and Resilience

Recovery and handling of large-scale central treatment plants during disaster events might be difficult, and their cumulative effect could be at a bigger scale. While OWTS in smaller scales can be easily managed, and the possible cumulative effects could be to the systems vicinity scale. For example, users might use some other external collection materials until systems return to normality. System recovery costs are also incomparable. Upon properly managed and inspected treatment results are quite reliable and optimal (Heistad, Paruch et al. 2006).

Aesthetic and Ecological considerations

Systems can be optimized to serve a wider function like educational, demonstrational and landscape aesthetics (Jenssen, Maehlum et al. 2005). CWs cloud possible be built in a way that fits the landscape with flowering plants and recreational grasses. The grown plants could harbor both faunal and floral organisms, which basically enhance ecosystem stability. Microorganisms in the media could facilitate rate of bio-decomposition and produce available nutrients for plants. Furthermore plants in return act as habitat and source of aeration. Besides, plants could basically be habitat to some faunal insects (e.g. bees and better fly), which could enhance honey production and crosspollinations.

2.4. Wastewater Source Separation & Volume reduction

Domestic wastewater can be separated into concentrated black wastewater from toilets (faeces and urine), and less concentrated grey wastewater that originates from showers, kitchens, washing basins, laundry and others sources (van Voorthuizen, Zwijnenburg et al. 2008; Murat Hocaoglu, Insel et al. 2010) as illustrated in (Fig3). Many studies report that black wastewater usually contains the majority of pathogens, valuable organics and nutrients, which can be used for agricultural purposes with proper treatment (Fig4&5). On the other hand, grey wastewater is characterized with lower organic concentrations and fewer pathogens than the combined domestic wastewater (Roeleveld, Elmitwalli et al. 2006; Murat Hocaoglu, Insel et al. 2010).

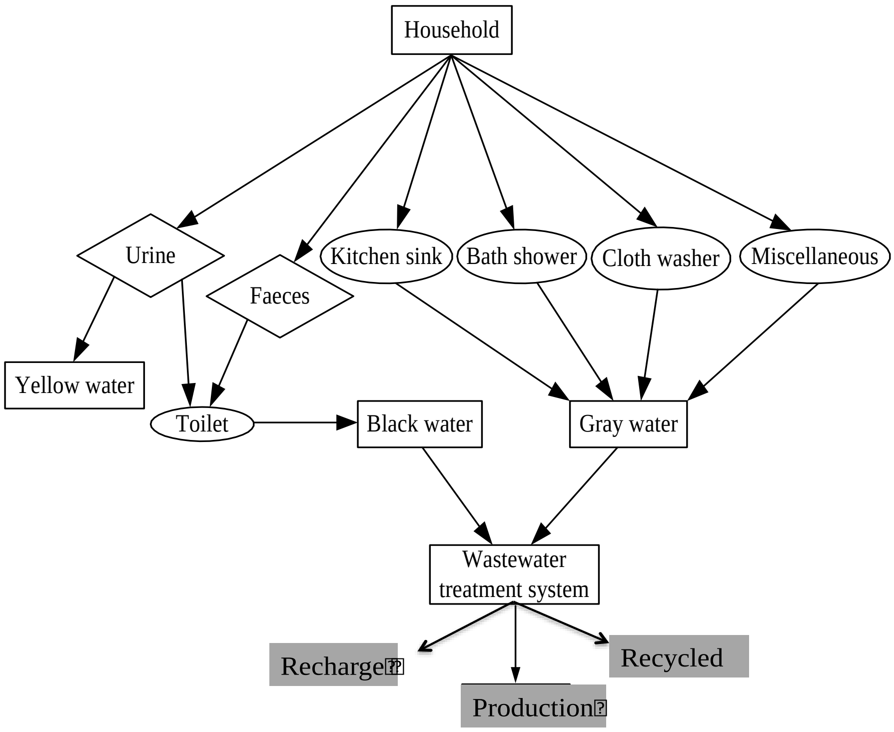


Figure 3. Household wastewater segregation according to their sources.

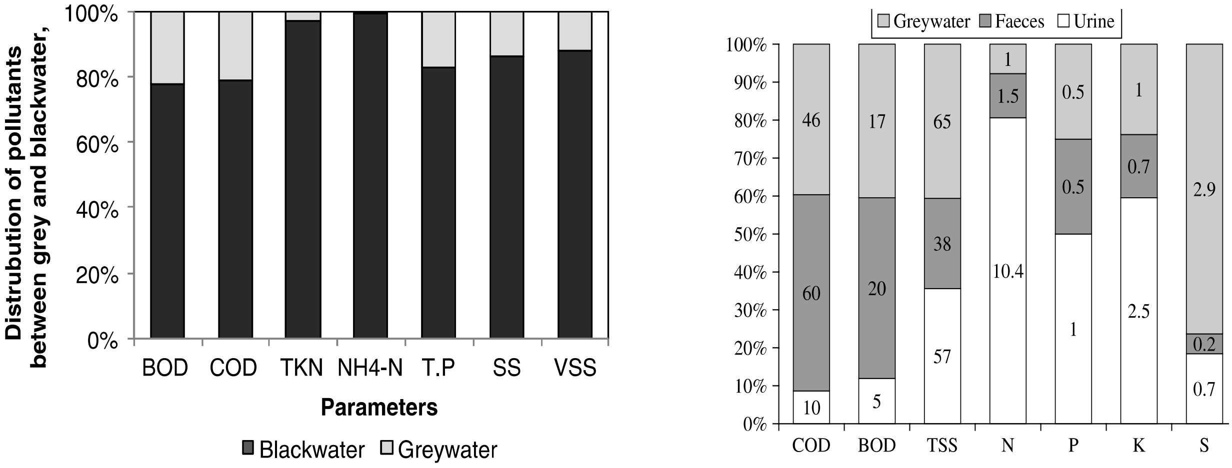
Source: adopted from(Nam 2006)

The philosophy of source separation of domestic wastewater fractions inevitably involves new and compatible approaches for treatment, utilization and safe disposal (Murat Hocaoglu, Insel et al. 2010). It is an approach aiming to separate wastewater fractions for more efficient treatment and reuse with the principles of Ecological Sanitation (EcoSan), closing the loop. This has an advantage in cost minimization and volume reduction as highlighted earlier. The reason is the grey water, that accounts much of domestic wastewater by volume and characterized with low pollutant concentration can easily be treated separately.

4.1.1. Black Wastewater Characterization

Domestic wastewater can be characterized with respect to physical, chemical and microorganism parameters (Metcalf & Eddy, Tchobanoglous et al. 2003; Davis 2010). Physically fresh, aerobic, black wastewater has been said to have the odor of kerosene or freshly turned earth. Whereas aged, septic sewage is considerably more offensive to the olfactory nerves (Davis 2010).

As it is clearly indicated in (Fig4 a), more than 80% of organic matter; SS, Tp and most of the nitrogen (99% of the NH4-N) in household wastewater comes from black wastewater. Considering separatlly (Fig4 b), faeces are characterized relativlly with higher BOD, COD and TSS content, while urine is characterized with higher content of nutrients (N, P and K). Incontrast, greywater is characterized with overall low content of contaminants in both (Fig4 a&b), though it accounts higher volum of the total household produced waste. That is why the motive wastes should be collected separately for different degree of treatments based on the nature and proporties of the wastes for efficiencient treatment and cost minimazitions is appreciated.



(a)　　　　　　　　　　(b)

Figure4. Distributions of source separated household wastewater fractions

Sources: [a](Murat Hocaoglu, Insel et al. 2010) and [b](Meinzinger 2009b)

The content of BOD and COD is very crucial in considering biological treatments. It indicates the degree of biodegradability, storability and sensibility of the waste, to sulphide production (odor) as it relates to the degree of oxygen depletion (Crites and Tchobanoglous 1998). The ratio of BOD/COD for untreated sewage typically range from 0.3 to 0.8 and if the ratio is 0.5 or greatre, it is considered to be easily treatable by biological means (Metcalf & Eddy, Tchobanoglous et al. 2003). In a study by (Palmquist and Hanaeus 2005), an average ratio of BOD_7/CODCr, 0.45 for blackwater and 0.71 for greywater was found. But a study by Murat Hocaoglu, Insel et al. (2010), BOD_5/COD ratios were found to be 0.28 & 0.38 for black and grey wasteater respectively. In which both studies was on similar grounds but variable results. Therefore, they concluds as a good indication for the unreliable nature of BOD_5 in reflecting the biodegradation trend of the organic by compairing with more other prior studies that found lower ratio of 0.44 on similar grounds. Another parametr for the household waste pollutant characterization might be also the possibility of of heavy metals as discussed in (*section 2.4.3* and Table3).

In a biological wastewater characterization, knoweldege of both the important microorganism for facilitating biological treament process and pathogens of concern are very crucial. Especially bateria, protezoa and fungi are of great interest as decomposers. They fill an indispensible ecological role of decaying organic matter in nature and in stablizing organic wastes in treatment palnts (Hammer and Mark J. Hammer 2008).

4.1.2. Wastewater Reuse Potentials

The current trend in wastewater treatment is not only about the removal of waste and health threats from reaching water bodies it is all about the effective ways of resources recovery while meeting local environmental discharge limits. Various reasons drive this motive, varying from limited abundance of specific resources to financial reasons, where recovering is fairly cheaper than extracting the raw resources.

In addition, wastes could be viewed as potential raw impute for productions like energy, nutrients and recycled water (Roeleveld, Elmitwalli et al. 2006; Meinzinger, Oldenburg et al. 2009b). For example, Roeleveld, Elmitwalli et al. (2006) estimates a potential energy production of 101 $kWh.y^{-1}.p^{-1}$ based on 122gCOD/d originating from a single person which is equivalent to 28L methane per day in anaerobic treatment methods. Chavez, Jimenez et al. (2004) also estimates a minimum of $108m^3s^{-1}$ of wastewater is used in Mexico for irrigating 254,000ha are very few examples.

It is well known that the limited resources for plant growth like nitrogen (N), phosphorus (P) and potassium (K) are present in substantial amount in household wastes that can enhance productivity (Roeleveld, Elmitwalli et al. 2006; Meinzinger, Oldenburg et al. 2009b). Properly treated sludge can be used as a phosphorus-enriched organic fertilizer, provided that it is safe regarding heavy metals and micro-pollutants. For examples a study by (Meinzinger, Oldenburg et al. 2009b) in Sodo, a province in Ethiopia shows 1.4 times higher productivity using urine as fertilizer compared to manufactured DAP- fertilized as shown in (Fig6) below.

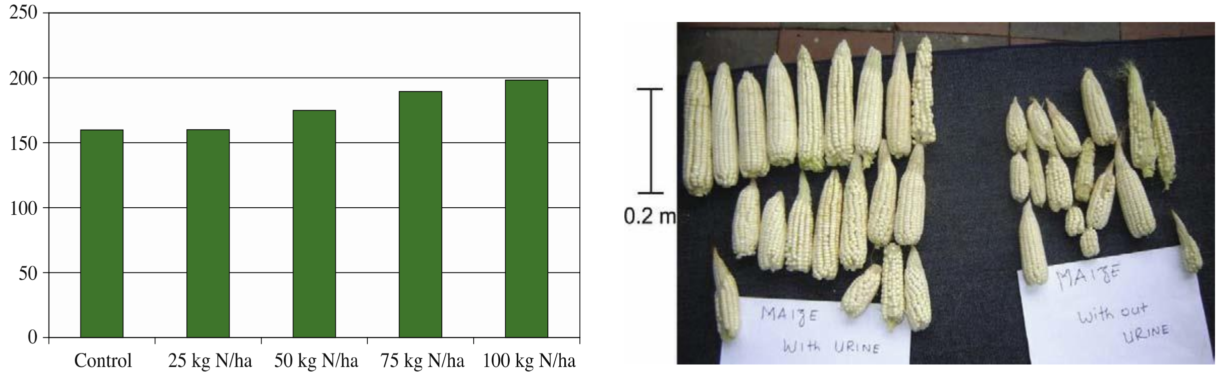


Figure 5. Potential nutrients in black wastewater for crop production

Source: (Meinzinger, Oldenburg et al. 2009b)

As the same time excess discharge of those nutrients to receiving water bodies result in serious eutrophication, that affect the general aquatic ecological balances. Hence, in response to that there are more and more environmental regulations for controlling nutrient discharge in receiving waters implemented in many countries, e.g., typical effluent standards that require N and P concentrations in effluent may be less than 3mgl^{-1} total Nitrogen and 1mgl^{-1}, respectively (Haandel and Lubbe 2007).

4.1.3. Cautions

Heavy metals

When it comes to wastewater reuse for irrigation and/or as fertilizers, attention should be paid for possible heavy metals. Palmquist and Hanaeus (2005) detected a total of 71 out of 105 selected potential hazardous substances in raw source separated grey and black-wastewater from ordinary Swedish households. Their possible sources could be during system installation and domestic use sources. Therefore, avoidance at source will be much productive than treatment.

Meinzinger and Oldenburg (2009a), carried out a desk study from 135 source separated wastewater scientific studies from over 20 countries mostly from Europe. The study lists (Table3) as the most possible and amount of heavy metals expected to exist in each urine, faeces and greywater. The table also summarizes the acceptable level of wastewater quality for irrigation application as summarized from (Roeleveld, Elmitwalli et al. (2006) in Asano and Levine 1998) for comparison.

Table 3. Heavy metals in source separated wastewater ($mgp^{-1}d^{-1}$) vs acceptable level for irrigation, mgl^{-1}

	Pb	Cd	Cu	Cr	Hg	Ni	Zn
Water quality for irrigation, $mgl^{-2\ a}$	-	0.01	0.1	0.2	0.2	5	2
Urine[b]	0.02 (++)	0.01(++)	0.01(++)	0.01(++)	0.01(++)	0.01(++)	0.30 (++)
Faeces[b]	0.02 (-)	0.01(+)	1.10(-)	0.02(-)	0.02(-)	0.07(+)	10.74(-)
Greywater[b]	3.00(+)	0.08(+)	6.50(+)	2.01(+)	0.02(-)	1.6(+)	23.26(+)

Data quality: - poor; + fair; ++ good. Sources: summarized from, [a](Asano and Levine 1998 in Roeleveld, Elmitwalli et al. (2006)), [b](Meinzinger and Oldenburg 2009a)

Microbial pathogens

Common human health threat pathogens are also a greater concern in improperly treated wastewater for reuse applications. Many infections intestinal diseases of humans are transmitted through fecal wastes (Hammer and Mark J. Hammer 2008). Pathogen in the faeces includes all major categories: bacteria, protozoa, virus and helminthes which and are critically health concerns in places where wastewater is used for irrigation and in areas where access to sanitation facilities are limited (Metcalf & Eddy, Tchobanoglous et al. 2003; Seidu, Heistad et al. 2008; Eggen 2011). Transmission is by the faeces of an infected person getting into the mouth of another person, referred to as the fecal-oral route and other routs could be contaminated finger or food and water (Hammer and Mark J. Hammer 2008).

Some sources and routes could possibly be faeces of diseased animals, insect vectors inhalation of dusts or aerosol droplets and a few worms can penetrate through the skin (Hammer and Mark J. Hammer 2008). Effective diseases control could be achieved by introducing a comprehensive environmental health program that incorporates personal and household hygiene, control of fly species and other insects, monitoring of food processing, proper waste disposal, protection of water sources and drinking water treatments, vaccination and immunization of infected people are some of the measures (Hammer and Mark J. Hammer 2008). OWTS systems, especially infiltration treatment technologies, are effective in removing pathogens through the combined effects of straining, adsorption and various limiting environmental factors (Ausland, Stevik et al. 2002; Stevik, Aa et al. 2004; Heistad, Scott et al. 2009a) and (Table2).

2.5. Media Clogging

Clogging is the threat and a commonly criticized phenomenon for OWTS sustainable applications. It is rather a complex and yet not clearly identified (Zhao, Zhu et al. 2009; Nivala, Knowles et al. 2012). Many correlated to the strength of the wastewater while others to the waste application patterns, loading rates and particulate solids over the dissolved ones. While, others still link it to media properties and influence of microorganisms accumulated on the surface that form biofilm growths and sealing, e.g. Meinzinger and Oldenburg (2009a). The details are discussed below:

2.5.1. Clogging and Ponding

Winter and Goetz (2003), differentiate ponding and clogging as, ponding of the surface directly after a loading cycle didn’t bring the system automatically into the category “Clogging”. Ponding has to last until the next loading took place so that the media air is disconnected from oxygen supply. This means during loading events, the applied waste might float above the surface media for a while, but that doesn’t mean necessarily the media is clogged. It rather takes time to percolate slowly depending on the available pore space for infiltration, look (*section 2.5.2).*

Filter medium at initial loadings has rapid infiltration rates, but it tends gradually to decrease with continued loading (Jenssen and Siegrist 1990). Hence, the media pore space start to fill with wastewater substrates, biophysical byproducts and microorganisms that form a layer called biofilm (biomat), usually develops on the infiltrative surface. This reduces the media pore space and creates flow barrier that restricts the desired rate of infiltration, which is commonly called clogging. Clogging is characterized by a decrease in treatment performance or hydraulic malfunctions such as ponding of wastewater on the surface of the system and bypass of untreated wastewater (Knowles, Dotro et al. 2011; Nivala, Knowles et al. 2012).

Paradoxically, this biofilm plays a role to improve treatment efficiency by creating unsaturated flow across the media. Because, it increases hydraulic retention time that promotes more contact between percolating effluents and porous media surfaces and clog mineralization (Siegrist, McCray et al. 2004). However, this clogging should not still change the system to anaerobic phase, that malfunction the system´s performance (Zhao, Zhu et al. 2009).

The rate of clogging and pounding is also highly influenced by the media grain seize distribution (porosity) (Jenssen and Siegrist 1990), wastewater concentration level and size (Levinel, Tchobanoglous et al. 1991; Adam, Krogstad et al. 2005; Zhao, Zhu et al. 2009), loading cycles and application patterns (Heistad, Paruch et al. 2006; Nivala, Knowles et al. 2012). Therefore, controlling the intensity of clogging is essential to maintain a desirable infiltration rate. Hence, the clogged zone controls the infiltration rate of the wastewater absorptions.

2.5.2. Clogging Stages

OWTS based on infiltration mechanisms may be characterized as have three major operational stages regarding the media`s hydraulic behavior and clogging (Siegrist, McCray et al. 2004)2001):

Stage1: - Pseudo-steady state:

This is characterized by a rapid percolation and early maturation startup period. Applied hydraulic load infiltrates the media in a non-uniform manner due to imperfect distribution networks and the fact that clean media for infiltration rate typically 10 to 100 times higher than the designed hydraulic loading rate. This phenomenon with continued effluent infiltration, media permeability decreases at the infiltrative surface due to accumulation of pore-filling waste constituents and becomes uniform across the available infiltrative surface (Zhao, Zhu et al. 2009; Knowles, Dotro et al. 2011) and declines the rate of infiltration substantially. This event may last for some months to a year or more and is termed as beginning of unsaturated flow and began well-established biochemical purifications, which continues to very high treatment efficiency that approaches a pseudo-steady state.

Stage2: - Clogging development

In this stage clogging utilized fully the available infiltrative surface in which infiltration rate gradually decreases. This stage normally continues for several years or during which the infiltration rate may continue to decline and ponding may develop and increase in height to float (García, Rousseau et al. 2007). Rousseau et al. (2005) in (Knowles, Dotro et al. 2011), also observed a similar conclusion in twelve subsurface wetlands in the U.K. which managed to consistently meet discharge standards despite exhibiting symptoms of heavy clogging. During this stage, capacity limited media may become exhausted, and treatment may decline (e.g. P sorption capacity may decline, and P breakthrough may occur (Siegrist, McCray et al. 2004).

Stage3: - phase of operation

In the final stage, the infiltration rate has substantially declined but the system may function hydraulically at lower acceptance loading rate for another 10 to 20 years of continues operation (Siegrist, McCray et al. 2004). However, it continues indefinitely when the system is continuously used and in the absence of permeability regeneration (e.g. resting) and eventually reaches an operation state where hydraulic failure can occur. This means the daily application rate exceeds the infiltration rate at time ´t´ and maintenance is required. Long-term resting can help to restore infiltration capacity but the rate of recovery, can be very slow particularly in cold climates (Siegrist, McCray et al. 2004).

2.5.3. Effect of filterable content on clogging

The cause and effect between clogging development and waste filterable content relationships can be noticed on the occurrence and distribution of clogging developments following the inlet vicinity. This is either horizontal gradient accumulation in solids from inlet to outlet due to the method of wastewater application, for example in horizontal subsurface CWs (Adam, Krogstad et al. 2005; García, Rousseau et al. 2007; Nivala, Knowles et al. 2012) or from surface to base in response to the development of the filterable content in the upper strata (Adam, Krogstad et al. 2007a; Nivala, Knowles et al. 2012) in vertical CWs. This indirectly shows the associations that obviously are characterized with higher suspended materials to be trapped in the inlets.

Moreover, Winter and Goetz (2003) and Zhao, Zhu et al. (2009) identifies clogging development tendencies correlated with waste strength and particle sizes of TSS and COD in which commonly trapped in the inlet infiltration surfaces. A study on 21 vertical flow CWs by Winter and Goetz (2003) on the rate of clogging tendencies observed different effects with the same loading rate but variable influent concentrations. Systems loaded with higher TSS concentrations showed higher clogging tendencies while the other did less. The study concluded filterable waste content not to exceed 100mgl^{-1} prior applications into soil absorption systems especially for particles >50μm which can lead to surface pore blocking. It was also advised COD and TSS loads not to exceed 20 and 5gm^{-2}d^{-1} respectively for VFCWs better performance under the Central Europe climatic conditions. On the other hand Zhao, Zhu et al. (2009) found higher clogging tendency with particulate feed than with dissolved feed loadings.

Studies by García, Rousseau et al. (2007) founds about 17% media porosity drop in a wetland system feed without pretreatment unlike 6% drop loaded with physicochemical pretreatment after 120 operational days. On the other hand, according to (García, Rousseau et al. 2007), a primary settled effluent and some other physicochemical pretreatment could extend the life of a horizontal subsurface flow treatments by approximately 10 years. Nevertheless, contributors of clogging are not only the inlet influent filterable content of the applied wastewater content but also sources summarized in (Table4).

2.5.4. Biofilm, Clogging and Treatment

The impact of direct physical pore block by particulate to the process of clogging is greater than that of clogging caused by biofilm growth (Zhao, Zhu et al. 2009). The contribution of biofilm to clogging is accelerating the rate of buildup clog. Volume reduction due to clogging is a process that depends on the growth rate of the microbial group considered, retained organics and inert solids and the decay of plants (García, Rousseau et al. 2007). Sources of accumulation could be from the applied wastewater (external sources) or else developed through process inside the media (internal accumulation) and induced during constructions (italicized) in (Table4).

As a result of the accumulations further biomass can be proliferate once microbes have colonized media surfaces. Several studies conclude that greater biofilm development occurs at the inlet region where the concentration of organic matter in the wastewater is greatest (Adam, Krogstad et al. 2005; García, Rousseau et al. 2007; Adam, Krogstad et al. 2007a; Nivala, Knowles et al. 2012). Thus results to over-production of voluminous extracellular polymer substances (EPS) with a sticky nature, which easily trap substrates pass by and can cause an intensive pore blocking (Winter and Goetz 2003).

Table 4. Internal and external sources of clogging.

Component	Intentional accumulation (external loads)	Incidental accumulation (internal loads)
Organic solids	• Wastewater solids	• Biomass growth • Plant roots • Biofilm and plant detritus • *Solids introduced during construction*
Inorganic solids	• Wastewater solids	• *Solids from chemical erosion of gravel*
	• Chemical precipitates	•*Solids introduced during construction*

Source: (Knowles, Dotro et al. 2011).

Generally biofilm treatment processes in the different treatment kinetics involves three broad activities as it is summarized from (Crites and Tchobanoglous 1998) and discussed in *section 2.5.1:*

- ❑ Initially, portion of the waste is oxidized to smaller sizes and some end products, which produces energy for cell maintenance and synthesis of new cell tissues.

- ❑ Simultaneously, some of the organic matter (OM) is converted to new cell tissue using the formed energy in the initial stage, where microorganisms are growing in number and absorbed size, and the attachment becomes bigger and bigger due microorganism sticky enzymatic nature.

- ❑ Finally the OM, in which the microorganisms are attached in mass as source of food depletes both in food content and oxygen due to much buildup in the external surface. Then, starvation and internal respiration (endogenous respiration) and/or stronger microbes predating on weaker ones becomes evident. Finally the formed bigger biofilms or flocks starts to detach, filled up the media pores and acted as internal filters in the filter medium that improves treatment efficiency while reducing the rate of infiltration.

However; one has to keep in mind that the role of biofilm growth for pollutant removal is very crucial. Biofilm formation as a combined result of (Table4) catalysed by nematode, protozoa, bacteriophage, plant uptake and biological assimilation enhances the treatment process by involving removal mechanisms as highlighted in (Table5).

2.5.5. Clogging Management

Over two decade studies reviewed byKnowles, Dotro et al. (2011) in the U.S., U.K., France and Germany concludes both hydraulic loading rate and solids loading rate need to be considered when designing systems to operate robustly. For example, Siegrist, McCray et al. (2004) suggested unsaturated flow condition can be achieved by limiting design loading rates to a small fraction of the soil`s saturated hydraulic conductivity (K_{sat}) (e.g. 1 to 5c/day loading rates which are 1 percent or less of the soil K_{sat}) in soil infiltration systems.

Another evident way to reduce bed clogging is to remove the influent particulate matter (García, Rousseau et al. 2007). In common practices for reducing the particulates the wastewater flows through septic tanks prior to applications of soil infiltrations or filter medias in CWs. However, the efficiency of this type of primary treatments for the removal of organic particulate solids is very limited, in the range of 30 to 40% in terms of BOD_5 (Metcalf & Eddy, Tchobanoglous et al. 2003). Another development (Heistad 2008) introduces a compact bio-filter as pretreatment unites aiming to enhance removal efficiency (>85% BOD_5) but it is with shorter service time, which is about five years or so for P removal.

Generally, clogging management in subsurface treatment wastelands falls in two categories, preventive and restoring strategies (Nivala, Knowles et al. 2012). Preventative strategies are aimed at delaying or minimizing the negative effects associated with clogging while restorative strategies focus with recovering of the system hydraulic problems or poor treatment efficiency. Some of the possible solutions as suggested by (Winter and Goetz 2003; Heistad, Paruch et al. 2006; García, Rousseau et al. 2007; Zhao, Zhu et al. 2009; Nivala, Knowles et al. 2012) are:

Preventative strategies:

- Incorporation of a pretreatment stage, which negates the impact of subsequent process upsets due to waste strength
- Use of an influent distributor that uniformly loads the wastewater over the maximum area possible
- Minimal influent concentration of solid loadings
- Changes to hydraulic operating conditions, intermittent dosing of the influent in surface loaded systems, which will encourage surface layer mineralization

- Reduction of unintentional solids spillover/overload from upstream processes

Restorative strategies:

- Filter media shifting and replacement
- Periodic resting and drying
- Introduction of earthworms to the fully clogged systems

Earthworms in overcoming clogging

Recent research developments at the Institute of Wastewater Management and Water Protection, Hamburg University of Technology (TUHH), unveil that removal efficiency in most wastewater parameters higher than 90% in subsurface CWs supported by earth worms (Chiarawatchai 2010). Sludge production on the surface was also reduced by 40% with earthworms. The study demonstrated that the vertical subsurface-flow constructed wetlands with earthworms followed by horizontal ones had generally the best treatment performance.

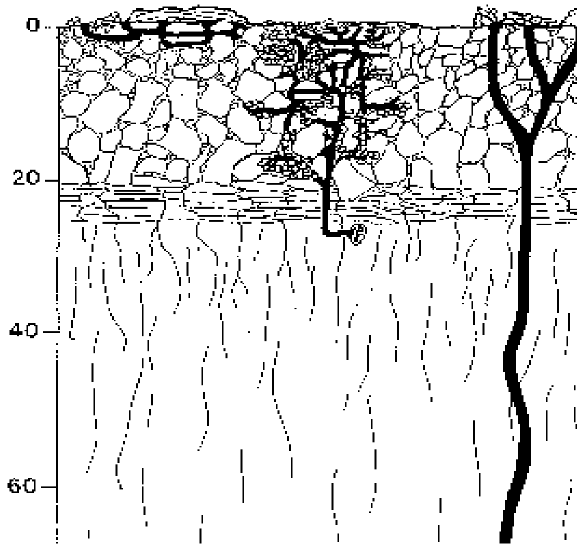


Figure 6. Earthworm burrowing patterns enhance aeration and rate of clog mineralization

Source: (Chiarawatchai 2010)

Similar studies in Australia by Davison et al. (2005) in (Nivala, Knowles et al. 2012) in horizontal subsurface flow (HSSF) treatment wetlands, found a reduction of the dry weight of the clog matter by an average of 56%. A most recent full-scale study on six fully clogged VF wetlands by Li et al. (2011) concluded that with the addition of 0.5kg/m^{-2} of earthworms clogging could be amended in ten days' time, without negatively impacting effluent water quality. The worms can also tolerate a temperature between 0-35°C in aerobic conditions.

2.6. Filtration

2.6.1. Definitions:

There are various context-based definitions of filtration. The definition given by Cheremisinoff (2002), “separation of suspended particulate matter from water”, interests most for this work. He elaborates further, “The act of passing the solution or suspension through a porous membrane or medium, by which the solid particles are retained on the medium´s surface or within the pores of the medium, while the fluid, referred to as the filtrate, passes through”.

Sutherland (2007), on the other hand defines filter medium as “any material that, under the operating conditions of the filter, is permeable to one or more components of a mixture, solution or suspension, and is impermeable to the remaining components”. In general, filtration is performed for one or both of the following reasons. It could be used for recovery of valuable products (either the suspended solids or the fluid), or it may be applied to purify the liquid stream, thereby improving product quality, or both (Cheremisinoff 2002). In which the interest in this study is to enhance both qualities.

2.6.2. Filtration mechanisms in fabrics, granular media and clog formation:

According to Cheremisinoff (2002) & (Fig7) there are four basic physical parameters that characterize a filter material to the system flow dynamics. These are porosity, permeability, tortuosity (the average flow path bends and length) and connectivity. Both Faure, Baudoin et al. (2006) and Cheremisinoff (2002) explained how the above mentioned properties affect the medium nature and clog formation; by referring to Stoke’s Law, particles with different density to wastewater will move vertically across the flow-field under the effect of gravity, until they impact a surface. Then after, non-uniform hydrodynamics forces across the body of a particle will cause it to drift across the flow-field. Particles with significant inertia may deviate from streamlines as flow diverges around obstacles, and impact a surface (Fig7e)

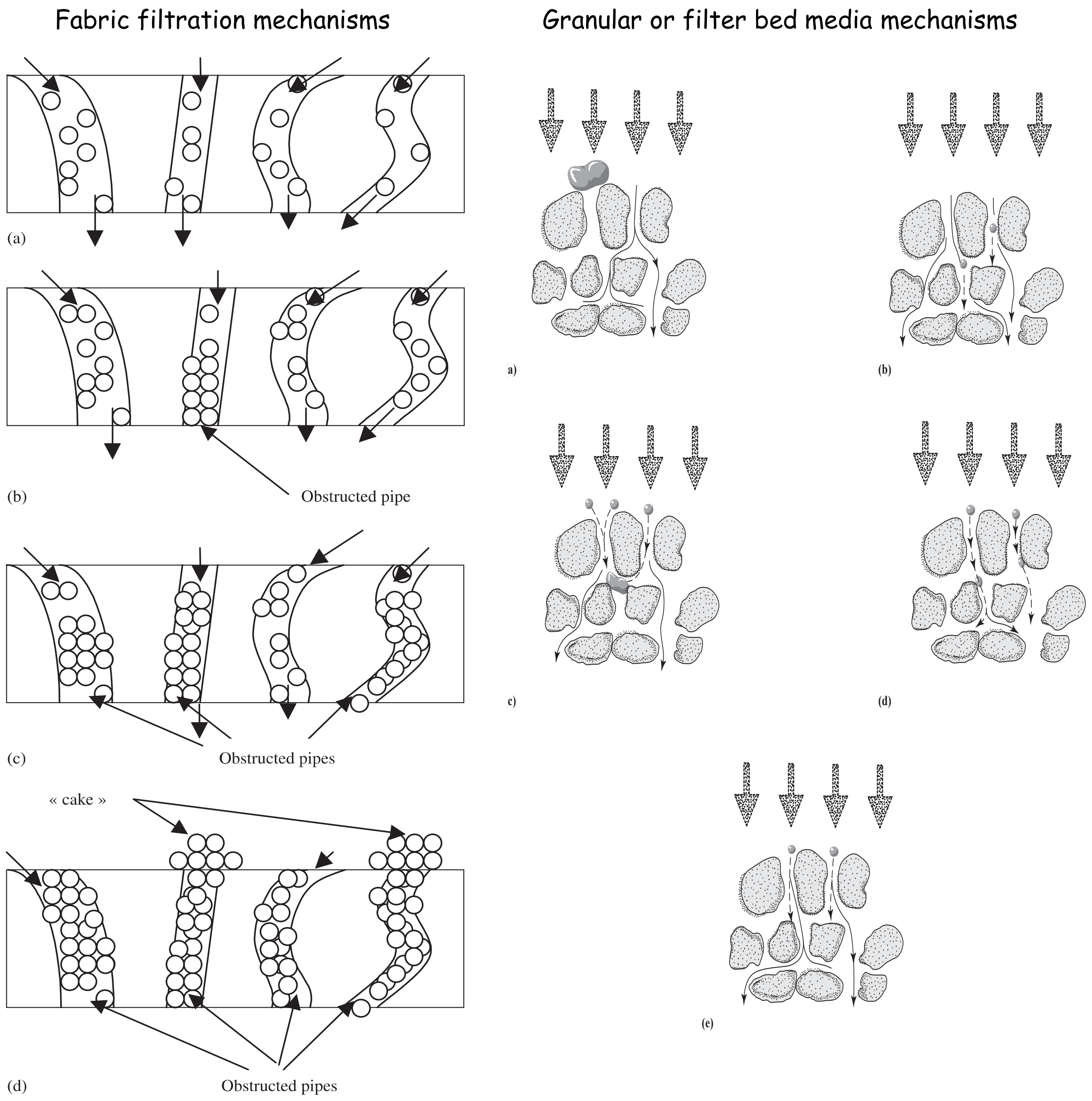


Figure 7. Mechanism of particles filtrations and accumulation in textile and granular media

Fig8. Mechanism of particles filtrations and accumulation: (a) all pipes are opened (no one is obstructed), (b) few pipes are obstructed, (c) Most of the pipes are obstructed and (d) Appearance of "cakes" above completely obstructed pipes. Source: (Faure, Baudoin et al. 2006)

(a) mechanical screening, (b) sedimentation, (c) flocculation, (d) interception and (e) impaction. Dashed line is particle trajectory. Solid line is water streamline (flow path).

If the streamline conveying a particle is closer than the radius of the particle interception of the media surface will occur and particles that are larger than the pore spaces will be strained (Winter and Goetz 2003), (Fig7 d and a) and particles may also be trapped by media morphological irregularities (Fig7b). Filamentous/fibrous particles are particularly susceptible to these modes of removal (Zhao, Zhu et al. 2009 and Nivala, Knowles et al. 2012).

Colloidal particles are influenced by the thermal forces responsible for Brownian motion, which induce random trajectory through the flow field. Repulsive or attractive forces between particles in suspension, and particles and media surfaces will influence particle trajectory.

Small particles can be removed within relatively large pores if numerous particles arrive simultaneously and block the pore by bridging (Winter and Goetz 2003)and (Fig7c). The coagulation of smaller colloids into larger particles promotes their removal through the mechanisms outlined in (Table5).

Table 5. Large and small size particle removal mechanisms in filtration

Large particle	
Sedimentation and buoyancy	According to Stoke's Law, particles with different density to wastewater will move vertically across the flow-field under the effect of gravity, until they impact a surface
Hydrodynamic effects	Non-uniform hydrodynamics forces across the body of a particle will cause it to drift across the flow-field
Inertial divergence	Particles with significant inertia may deviate from streamlines as flow diverges around obstacles, and impact a surface
Interception	If the streamline conveying a particle is closer than the radius of the particle interception of the media surface will occur
Straining and trapping	Particles that are larger than pore spaces will be strained and particles may also be trapped by media morphological irregularities. Filamentous/fibrous particles are particularly susceptible to these modes of removal
Small particle	
Brownian motion	Colloidal particles are influenced by the thermal forces responsible for Brownian motion which induce random trajectory through the flow field
Electrostatic forces	Repulsive or attractive forces between particles in suspension, and particles and media surfaces will influence particle trajectory
Bridging	Small particles can be removed within relatively large pores if numerous particles arrive simultaneously and block the pore by bridging
Coagulation	The coagulation of smaller colloids into larger particles promotes their removal through the previously outlined mechanisms

Source: (Knowles, Dotro et al. 2011)

Cheremisinoff (2002) explains ffiltering starts with the trapping of the larger suspended particles at the surface or at some depth. Individual particles may be blocked in the pores or several particles may interact to form a bridge in the pore that prevents further movement of these particles in the direction of flow. Once movement of the larger suspended particles has been blocked, these particles themselves begin to function as a filter and trap successively smaller suspended particles (Knowles, Dotro et al. 2011). According to Cheremisinoff (2002) filter media can be classified into several groups, but the most common classes are surface and depth type:

Surface/Cake filtration

In this type of treatment waste constituents are mostly retained on the medium´s surface. That is, bigger size particles that can’t penetrate into the pores retain on the surface. In this type of filtration there is a possibility of increasing in treatment quality as the retained wastes can serve as filters. Filter papers, filter cloths and wire mesh are such common examples of this type.

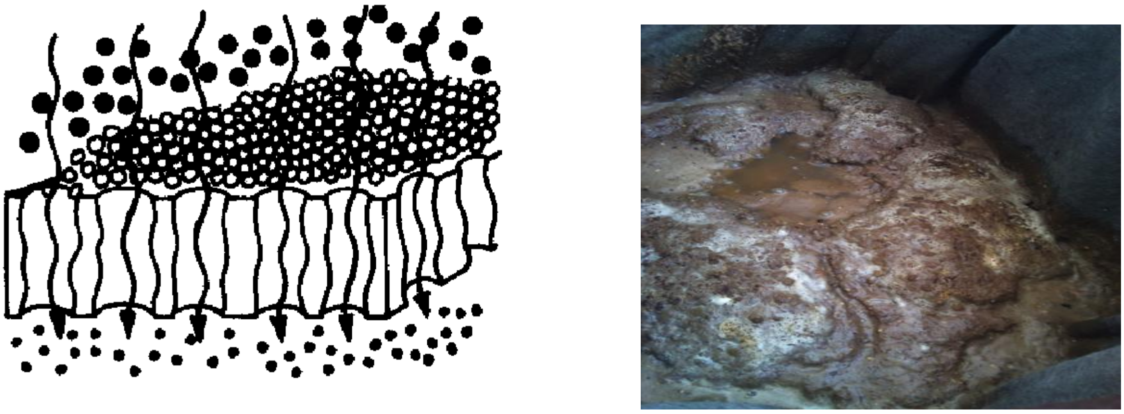


Figure 8. Cake filtration

Source: Sutherland (2007)

Depth filtration

Depth type filter mediums are commonly used for wastewater clarification purposes and characterized as the solid particles penetrate into the pore where they are retained. The particles retained on the walls of the pores by adsorption, settling, and sticking (Winter and Goetz 2003; Sutherland 2007) and (Fig9). Cheremisinoff (2002), further explains depth type filter media retaining efficiencies are between 90 and 99%. Some filter media can be either surface-type or depth-type, depending on the pore size and suspension properties (e.g., particle size, solid concentration and suspension viscosity)

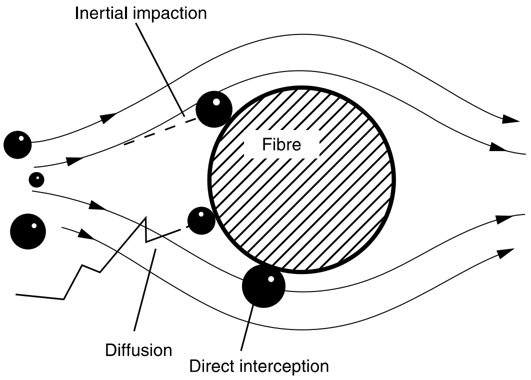


Figure 9. Depth filtration

Source: Sutherland (2007)

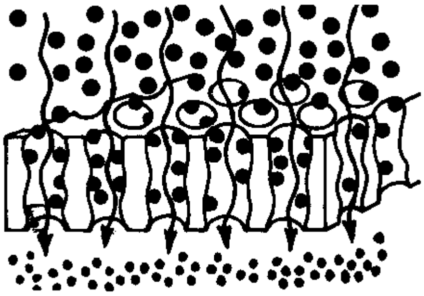


Figure 1.6 Depth filtration

2.6.3. Fabric Filter Selection Criterion

Cheremisinoff (2002) concludes that there is no generalized formula for selection of a filter media that is independent of the details of the intended application. An ideal filter media must incorporate a maximum size of pores while as the same time providing a sufficiently pure filtrate. However, fulfillment of this rule invokes difficulties because of the increase or decrease of the pore size acts in the opposite way on the filtration rate and solid retention capacity. This is because there are several other requirements that cannot be achieved through the selection of a single medium (Sutherland (2007).

In general, regardless of the specific application filter media permeability of the medium relative to a pure liquid, its retention capacity relative to solid particles of known size and the pore size distribution are the most common ones. Selection of multi filters media with varied properties could help to meet the desired filters. To be effective in filtration and related separation processes, the fabric must be chemically resistant to both the feed and cleaning fluids, mechanically and thermally stable, high permeability whether as appropriate and stable in operation for prolonged periods (Sutherland 2007).

CHAPTER 3

Materials and Methodology

3.1. Experimental setup

The study was a laboratory scale experimental test. The experiment was set out at the Norwegian University of Life Science (UMB), Mathematical Sciences and Technology (IMT) department´s experimental station in two phases. The first phase was devoted to pre-tests conducted in columns (Fig13) to determine the feasibility of the filters and gain insights on the properties of the textile filters. The second phase was a full-scale application on the actual BoxFilters (Fig14). Laboratory analysis was carried out at the Plant and Environmental Sciences (IPM) department.

The experimental station is connected to the University students' dormitories (Kaja) with pressurized pipeline (about 150m) to a source separated black wastewater generated from low flushing vacuum toilets, used for this experiment. The experiment extended for about five months in the first phase and a month and half (21 Aug to 01 Oct 2012) for the second full-scale with different loading and resting intervals. Loading rates were simulated on the assumption of an average black wastewater a single person can produce and intervals to visit a toilet per day in the Norwegian context.

3.1.1. Column experiment *(phase1)*

The performance of three fabric filters on four columns with one column the same fabric but filled with sawdust to 15cm (Fig10 & Table6), was studied. Columns were loaded with pre-programmed loading rates, after a thorough auto mixing in the holding tank to the column top opening and covered with textile filters from the bottom to drain by the force of gravity. Both experiments were also subjected to variable drying periods (drying-wetting, resting periods) to mimic the actual phenomena in real applications. The assumption is that if the systems are applied in remote tourist sites and summerhouse, which are basically used occasionally and seasonally.

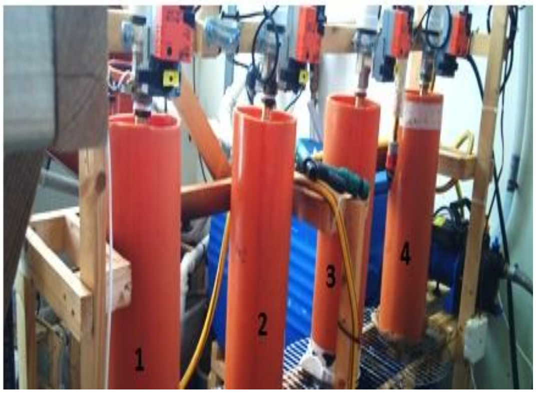


Figure 10. Experimental setup and column labeling

Table 6. Column labeling and representing

Labeling	*Stands for*	*Comment /content*
C_0	Zero sample	Raw influent
C_1	Colum 1	Textile 1
C_2	Colum 2	Textile 2
C_3	Colum 3	Textile 3
C^*_4	Colum 4	Textile 2 filled saw dust (15cm)

Note: * exists only to the column experiment not in FilterBox

3.1.2. Full-scale experiment, FilterBox *(phase2)*

The FilterBoxes are specially designed (Fig14) for draining from the bottom and the sides with a special handling both for heavy lifting and a separated compartment to shift filters that are clogged inside the big box (Fig14-covered with fabric filters).

Figure 11. Full-scale application (the FilterBox)

3.2. Hydraulic loadings and loading patterns

Each setup was made of pvc tube columns of 164mm diameter and around 50cm in height. Loading rate was set automatically to a single loading (i.e. three flushes of 0,9L each) a day (2.7L) each column, with one-day residence time**.** These loadings were continues loading except during the drying and resting periods were columns are free of load. Columns were also loaded manually after the full-scale started side by side with the full scale FilterBoxes.

The FilterBoxes were loaded with higher rates than the column experiments but not in a continuous loading. FilterBoxs were loaded with PLC controlled loading intervals that were simulating a diurnal distribution of toilet flushes from a residential application of JETS^{TM} VOD^{TM} vacuum sanitation system having 0.9 Liter flushing volume. They were loaded two times a week with eight loading a day, which is totally 21.6L.

Table 7. Loading intervals and hydraulic load that has been applied on two-subsequent days per week

Loading time	Number of simulated toilet flushes	Load (Liter)
04:00	3	2.7
08:00	3	2.7
08:15	3	2.7
12:00	3	2.7
15:00	3	2.7
16:00	3	2.7
18:00	3	2.7
18:15	3	2.7
Total	**24**	**21.6**

3.3. The textile filters module

The textile filters used in the experiment were commonly known as nonwoven polypropylene (textile 1&3) and woven Jute sack (textile2). The textiles are ISO standards certified to each specific parameters, with a predicted durability of 25 years in the range 4<pH<9 and temperature <25°C. Their detail corresponding properties are summarized in (Appendix3), as provided by the company supplier.

Figure 12. The textile filters used in the study

3.4. Process description and Sampling methods

Samples were collected both from the zero sample before filtration and after infiltration. Samples from the raw waste were collected from the collection tank (C_0). And samples after passing the textile filters (effluent) were collected at the bottom collecting plastic container for each experiment. Effluent samples were collected after a thorough manual mixing (staring) and analyzed immediately to avoid changes. However, extra samples were also preserved for backup in case unrepresentative results would appear. Sampling sources were emptied after taking samples for the next fresh samples sources. Plastic bottles used for transporting samples from experimental station to laboratory were washed properly with acid contain detergents to avoid changes.

Filtration rates were noted by timing and measuring the wastewater head loss through the experiments. Head loss measuring intervals were varying from minutes, hours to days depending on the rate of infiltration and clogging. Detail clogging development on the textile filters was noted and pictured during sampling periods.

A vertical column sludge extraction was also carried out gently, using pipettes to avoid stratification disturbance. This helps to observe how the particulate matter deposits inside the columns sludge and to assess either pH or temperature varies with change in depth of the accumulated wastes, especially in the column experiment which was narrow and deep. The aim was to see if anaerobic condition occurs, a rotten egg smell and black color formation (metallic sulfides, indication of anaerobic condition, (Metcalf & Eddy, Tchobanoglous et al. 2003); which potentially cause P- release and organic matter decomposition to fine particles. Knowing this will potentially help to make some design modifications if similar systems to apply in larger volumes.

3.5. Analytical parameters & procedures

Wastewater parameters, which commonly contribute to media clogging like total solids (TS), TSS, total dissolved solids (TDS) and fixed/volatile solids were analyzed according to the American Public Health Association (APHA) *standard methods for examination of water and wastewater* (APHA 2005) and HACH LANGE chemicals- www.hach-lange.com (consisting of spectrophotometer, thermostat and cuvette tests), (Table7). Dissolved and suspended matter was fractionated by suction filtration through 0.45-µm Whatman filter papers. BOD_5, COD and total Phosphorus (Tp) were determined from homogenized non-filtered samples but dissolved phosphate (orthophosphate, Op) was analyzed after 0.45µm filtration. Both Tp and Op were diluted to 1:20 while COD was diluted to 1:10 and BOD_5 to 1:2 ratios to bring in the chemicals measuring range by trial and error. Direct measurements like pH, temperature, infiltration rate (using measuring tape as dropped in height) after loading, clog development and other physical observations were noted and pictured during sampling. Temperature and pH measurements were conducted in the raw effluent on the assumption that much changes couldn't occur within the shorter loading and sampling events.

Table 8. Standards methods for laboratory analysis

Parameter	***Method***
BOD_5	OxiTop®
COD	HACH LANGE /LCK014
Tp	HACH LANGE /LCK350
Op	HACH LANGE /LCK350
TS	Standard Methods 2540B
TSS	Standard Methods 2540D
Volatile suspender solids (TVS)	Standard Method 2540E

3.6. Statistical Analysis

(Mæhlum 1998) point out that random and systematic variation of influent and effluent wastewater can be expected as a result of change in the composition of the raw wastewater, climatic influence and change in the filter media. Thus, during reporting it is wise that results show the whole nature of the data distribution.

In doing so, data analysis was handled mainly using Minitab16 and Excel office 2010. Box plots were selected for statistical summaries, as it is primal in showing the whole data nature. It shows five summaries at a time: the smallest observation (sample minimum), lower quartile (Q1), median (Q2), upper quartile (Q3), and largest observation (sample maximum). Each box represents the data for one of the major column/box categories. The length of the boxes indicate the 25th and 75th percentiles of the data; the line inside the box marks the value of the 50th percentile (median), and the circular dots show the sample mean value. Both the lower and upper whisker lines represent the sample minimum and maximum respectively. Overlapping box plots indirectly indicate no significant differences in their corresponding values. Trend analysis was also carried out to examine the filters response to clogging and sludge accumulation over time.

Analyses of variance (ANOVA) were also used to identify the removal differences between the different parameters and textile filters to assess the filter performance among each other. The reason why one way ANOVA was selected over the other tests was that, samples were independent (not paired or different sample sizes), data are obtained via simple random sampling, samples come from populations that are approximately normally distributed and populations have the same variance. However, Minitab is robust to samples coming from little varied population variance and normality. But normality test is carried out in case where it need test in this study. Generally, the differences between the inlet influent and filtrated effluent concentration were assumed to be the removal potential of the textile filters.

Chapter 4

Results

4.1. Introduction

The chapter presents the major activities and findings in this study. It starts with the general physiochemical characterization of both the influent black wastewater and the textile filters. This is followed by detailed analysis of removal capacities of the filters to the parameters outlined in the methodology. Clogging developments and infiltration capacities of the filters are also presented. Finally, the chapter provides possible insights for application in onsite treatment technologies.

4.2. Physiochemical characterizations

4.1.1. pH and Temperature

pH and temperature are the most important parameters in wastewater characterization as they affect the state of the wastes through process. The influent black wastewater in this study is characterized by an average temperature of (19.7°C, *n=18*) and a pH of (7.9, n=18), (Fig15). This range is in line with the standard domestic wastewater ranges (6.5-8.5) for pH (Metcalf & Eddy, Tchobanoglous et al. 2003). Generally, the pH and temperature range during the experimental time was stable. Little variation in temperature was measured in late August and early September (23.4°C) compared to the average range of (19.7°C) during the whole experimental period.

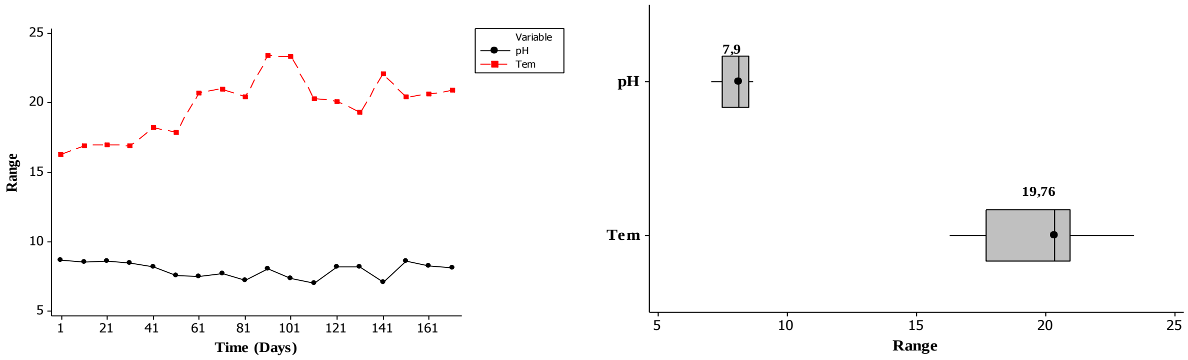


Figure 13. The pH and temperature ranges

High temperature is normally expected in domestic wastewater induced from the sources. This is because sources are expected to be warm (urine and feaces) in black wastewater and sources from shower and washers for grey wastewater (Davis 2010). Besides, undertaking this study during wormer season of summer in Norway could result in slightly higher temperature and pH. This, in turn, might also contribute to minor increase in biodegradation rates. The implication is that particulate size could reduce to pass the textile filters pore opening and may play a role for higher concentrations in the effluent.

4.1.2. Textiles physical property

Texture and flexibility

The textiles detailed property and physical appearances are summarized in (Appendix3) and (Fig14) respectively. Textile1 had a soft, flexible and fine hairy property compared to textile3, where it is characterized as thick, fairly hard and dense. Textile2 had bigger pore opening visible to the naked eye compared to the other two textiles and better flexibility than textile3.

Reaction to initial loadings

Textile2 is characterized by rapid initial infiltration rates compared to both textile1&3, followed by textile1. This rapid reaction to initial loads also holds true to reactions after resting and drying periods in the column experiment, as it was subjected for drying and wetting events. Based on the observed amount of drained effluent to the collecting bottom of each experiment, filter1 seemed to follow filter2. Textile2 filled with saw dust, showed similar property as the other textiles (1&3), even less incidents to clogging and ponding. Over a longer loading perspective, textile2 performed higher filtration rate (flux) compared to the other two (Fig24).

Particulate retaining

Compared to textile1, 2 and C_4, textile2 trapped less particulate matter in the initial three loadings as the filter bottom surface in textile2 was visible and transparent, while in the others it was covered with trapped suspended particulates (Appendix5.1b). This less initial retaining in textile2 might be related to the considerable pore opening that played an advantage for higher flux but in the opposite for waste constituent removal. Furthermore, there was no such visible physical differences between textile1&3, except much a thicker sludge accumulation inside C_3 during a vertical extraction using pipette.

4.1.3. The Raw black wastewater Characterization

The influent black wastewater used in this study can be characterized as highly concentrated. It had an average concentration of 12,500mgl^{-1}COD; n=27, 5363 mgl^{-1}BOD$_5$; n=2, 7500mgl^{-1}TS; n=24, 5000mgl^{-1}TSS; n=26, (Table9) and their corresponding 95% CI ranges in (Fig14) except for BOD$_5$ which had low sampling size to summarized in the figure.

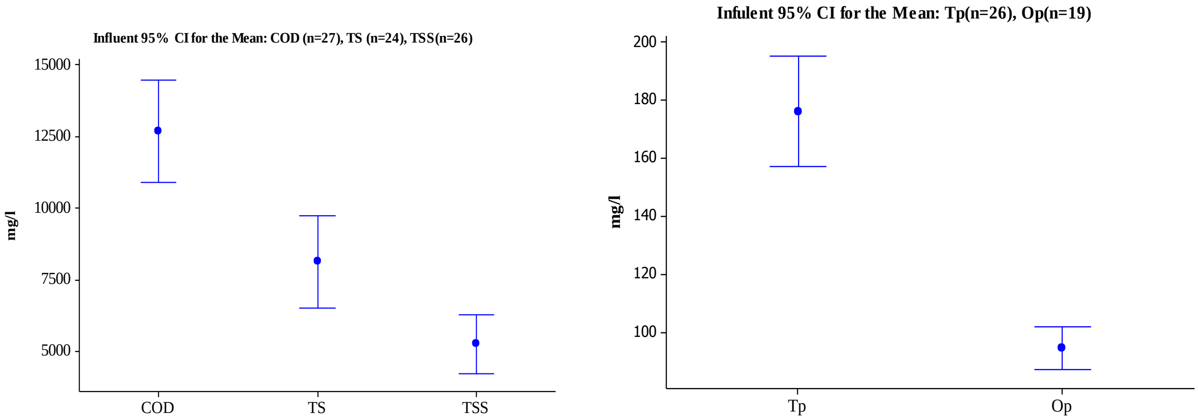


Figure 14. Influent concentration characterizations

The raw concentration is quite high compared to the typical household concentrations which is 1000mgl^{-1} for COD, 1200mgl^{-1} for TS, 350mgl^{-1} for TSS and 15mgl^{-1} for Tp categorized as strong household waste (Metcalf & Eddy, Tchobanoglous et al. 2003), though these might not be source separated and possibly not low flushing toilet sources. A lesser concentration is also reported, e.g., average COD values of 1139mgl^{-1}, 121mgl^{-1}Tp and 27mgl^{-1}Op by (van Voorthuizen, Zwijnenburg et al. 2008) from black wastewater with 5L flushing toilets. However, Roeleveld, Elmitwalli et al. (2006) from low flushing toilets (1L) reported (9.5-12.3gl^{-1}COD and 0.09-0.14 g1^{-1}Tp), with similar properties as in this study (Table9).

Table 9. Descriptive summary of the influent wastewater

Raw	N	Mean	Min	Q$_1$	Median	Q$_3$	Max
BOD$_5$	3	5363(±595)	4742	4742	5420	5928	5928
COD	27	12678(±4491)	5930	9033	11105	15150	22210
TS	24	8114(±3832)	1927	5600	6452	10115	16397
TSS	26	5237(±2575)	1740	3000	4270	7740	9520
Tp	26	175.9(47,18)	119,20	141.7	168,00	217,87	324,00
Op	19	94.3(±15,26)	63,60	89.80	84,60	109,60	120,00

4.2. Textile filters performance & pollutant removal capacities

4.2.1. COD and BOD_5 Removal

BOD_5

Though due to smaller sample size the representation of the results are questionable, it was observed a percentage reduction of about 41.5% in textile1 (n=2), 38.9% in textile3 (n=1) and 43.16% in textile3 (n=2) as it measured form the FilterBox experiments.

COD

COD performance trend over time to loadings (Fig15a&b) and removal potential (Fig15c&d), both in the column and FilterBox experiments are summarized in Fig17. The influent wastewater shows an overall variability and fluctuation compared to the effluents over the study period. Particular fluctuations were also observed in the column experiment compared to the FilterBox. The fluctuations in the column experiment might be related to the effect of periodic resting and drying. Though filter2 is characterized with considerable bigger pore opening, except in the early loadings in both experiments, it shows more or less stable and similar trends as in the other textile filters.

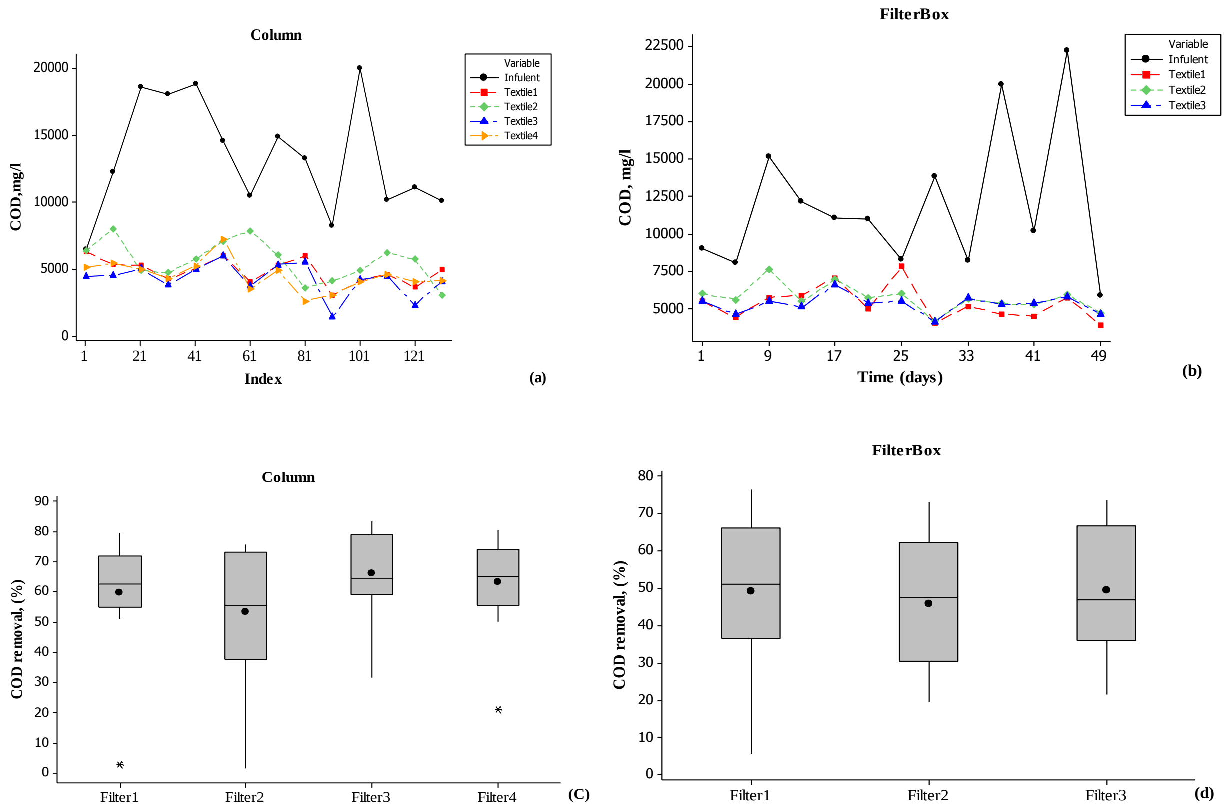


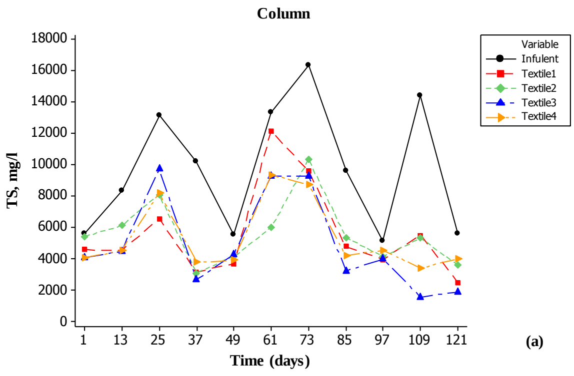
Figure 15. COD percentage removal and trends

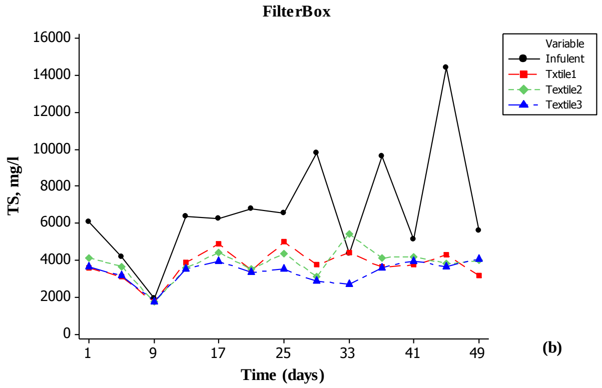
The textiles have an overall COD removal potential ranging from 40-80% and a median of 55% reduction as can be seen in the FilterBox, which is less than the column experiment about median of 65% (Fig15c and d). This higher performance tendency in the column experiment could possibly due to higher buildup of retained suspended matter acted as internal filters because of its impermeable pvs side walls unlike the FilterBox, where it has side openings for filtration. This might lead to surface to side filtration than filtering only over the accumulated suspended matter that act as extra filter in columns.

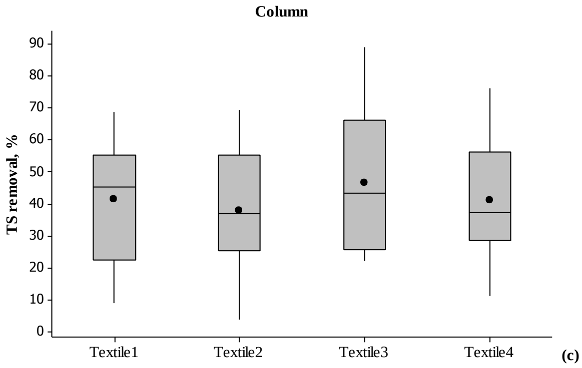
4.2.2. Suspended solids removal

TS

The inlet concentration in both experiments and effluent from the column experiment showed considerable fluctuations. The response of the textile filters to loadings over time fluctuated with the influent variation in the column experiment by contrast; there was a stable performance (Fig 16a and b) in the FilterBox experiment. Removal potential was found to be in the ranges of 20-60% in both experiments with median removal ranging from 35-455%. One can see the whisker plot overlapping in all filters in both experiments, which indirectly shows no considerable difference in between the textile filters.







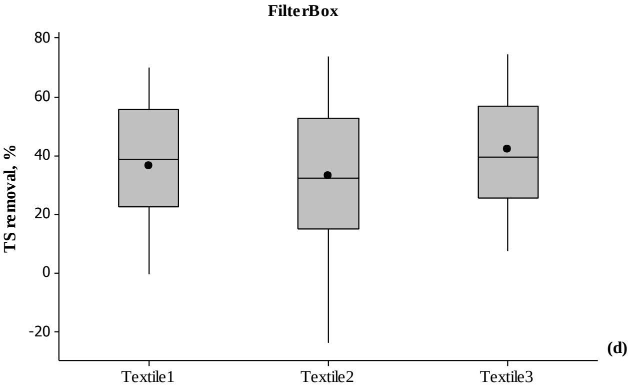


Figure 16. TS removal potential and trends

TSS

The textiles have a median removal capacity around 70%; and a little lower performance of about 40% was observed in textile2 in the FilterBox experiment (Fig17d). Performance trends tend to oscillate with the inlet variations in the early loading for textile2 and during the resting periods of all textiles in the column experiment.

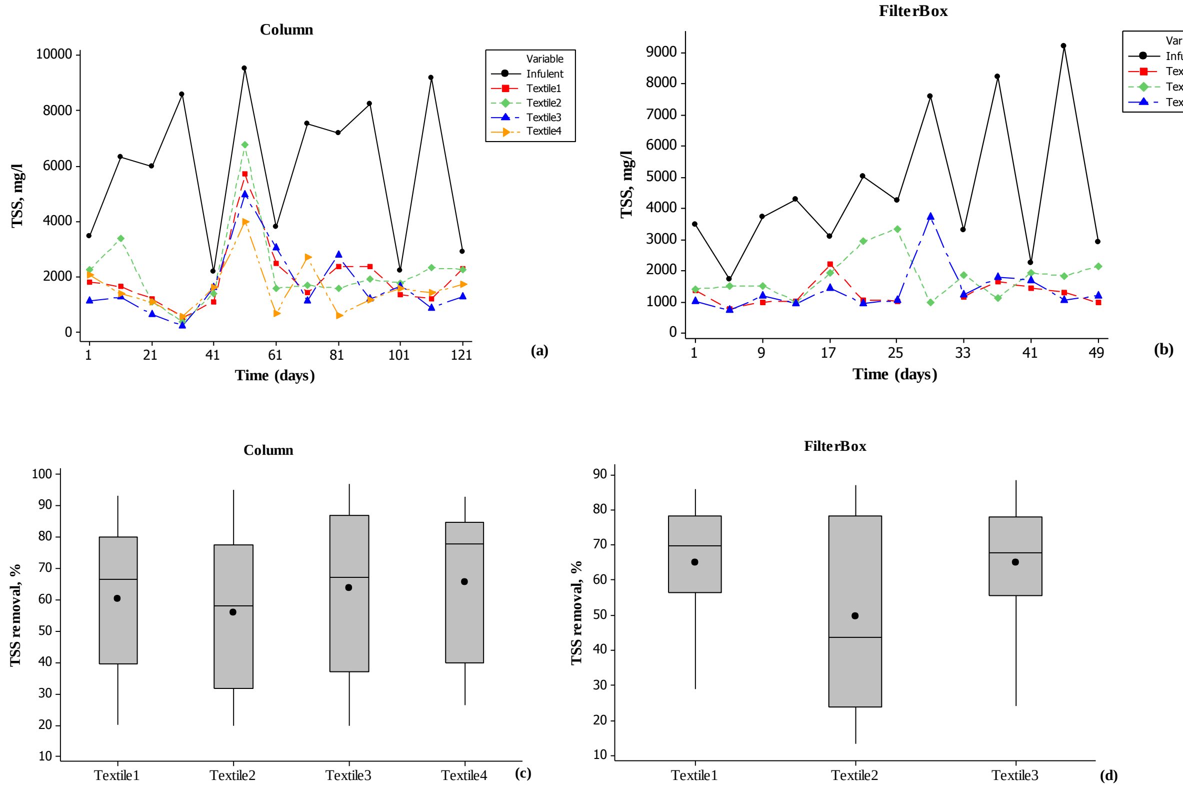


Figure 17. TSS removal and trends

Unlike the other two textiles, textile2 in (Fig17d) seemed to respond the removal potential in quite wider range and lower performance. As can be seen the individual samples in (Fig18), it ranges from below 20% to above 85% in almost all the sample values for textile2, unlike the outlines; one outlier account around 25% for textile3 and two outliers ranging 30-36% in textile1. This phenomenon didn’t occur in the column. Because in the columns the accumulated sludge might regulate the performances, while in the FilterBox side filtration is a possibility.

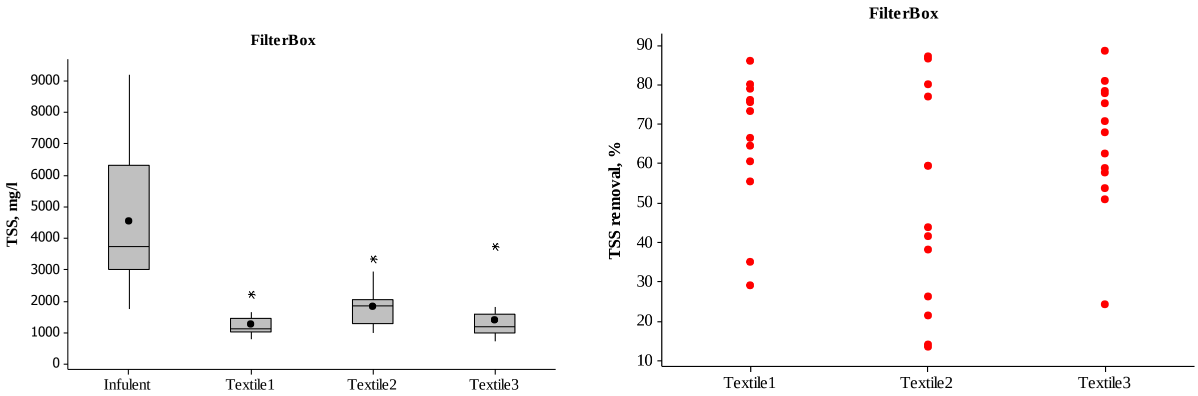


Figure 18. Textile2 VS textile1&3 individual value plot

TVS

A potential above 60% removal was observed both in textile1 &2, while slightly lower and close to 45% removal and wider range performance was measured in textile filter3 in the FilterBox Experiment as summarized in (Fig19).

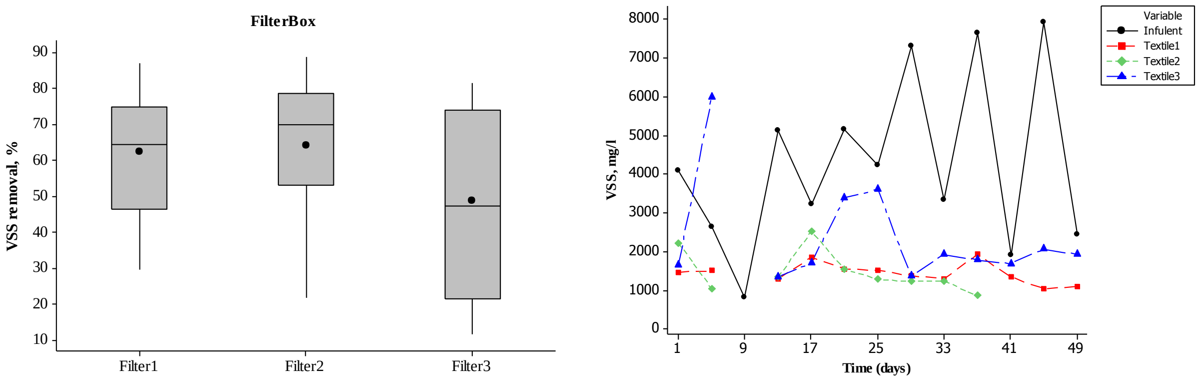


Figure 19. VSS removal and trends

4.2.3. Phosphorus Removal

Generally, phosphorus is categorized as Orthophosphate, polyphosphate and organic phosphate ((Davis 2010). Phosphorus in sewage is presented predominantly in the form of ortho-phosphates, with a minor fraction of organic phosphate incorporated in proteins. In a wastewater sludge, most of the organic-phosphors are mineralized, and orthophosphate is expected to dominate in the effluent (Haandel and Lubbe 2007).

Tp

In the raw influent, the concentration of Tp accounts about 168mgl^{-1}, n=26; (Table9). The overall trend in the column showed much fluctuation than the FilterBox experiment for the prior explained reasons, that are drying and resting events. The filters have removal potential ranging from about -10 in column experiment (textile3) to over 45% on the same experiment. Nevertheless, the textiles have a median removal capacity around 20-25% in both experiments (Fig 20).

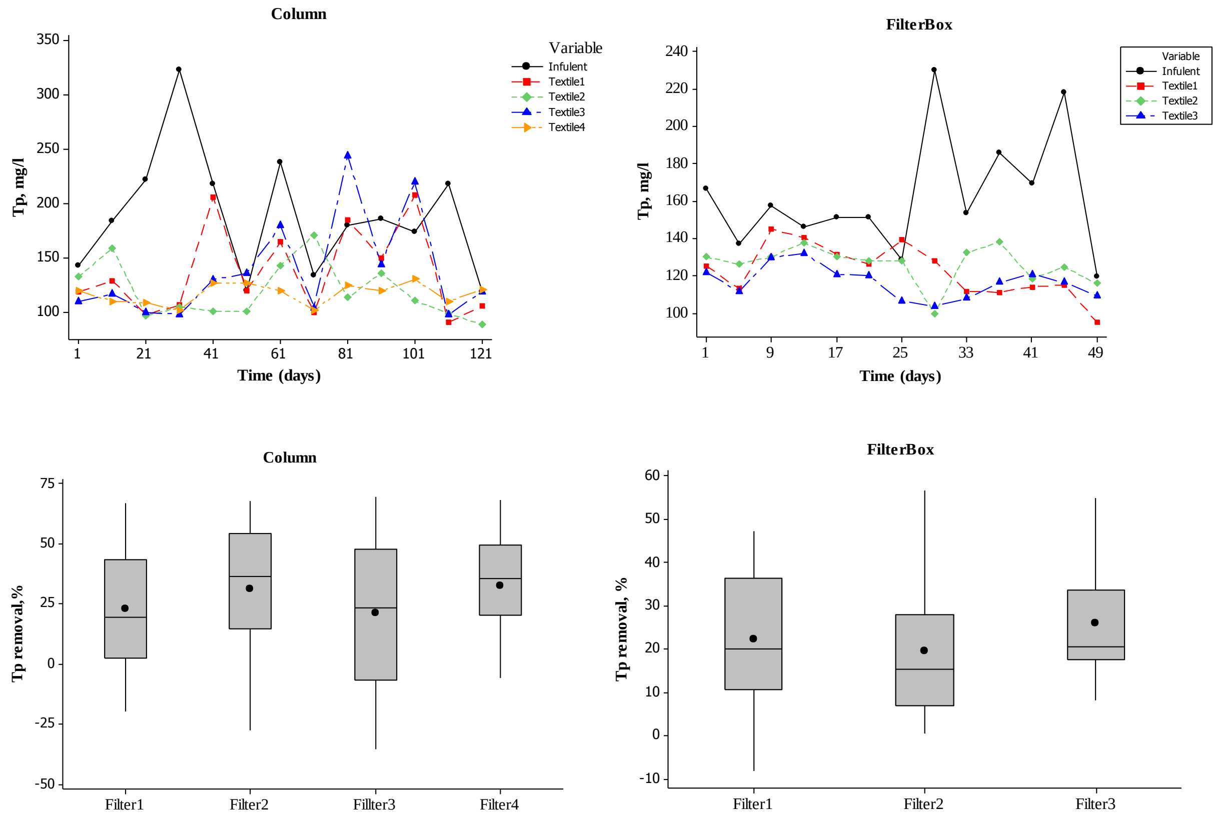


Figure 20. Total phosphorus removal and trends

Op

The median concentration of Op in the raw influent accounted 84.60mgl^{-1} (Table9). In regard to Op removal capacities of the filters, there seems to be no differences between the inlet and outlet wastes (Appendix 6 and Fig21). In fact, in some of the experiments it appears to increase more than the inlet concentrations, especially in filter1&2 in the column experiment. It also shows a tendency of better treatment in textile 2 and C4, which are characterized by bigger opening and filled with saw dust.

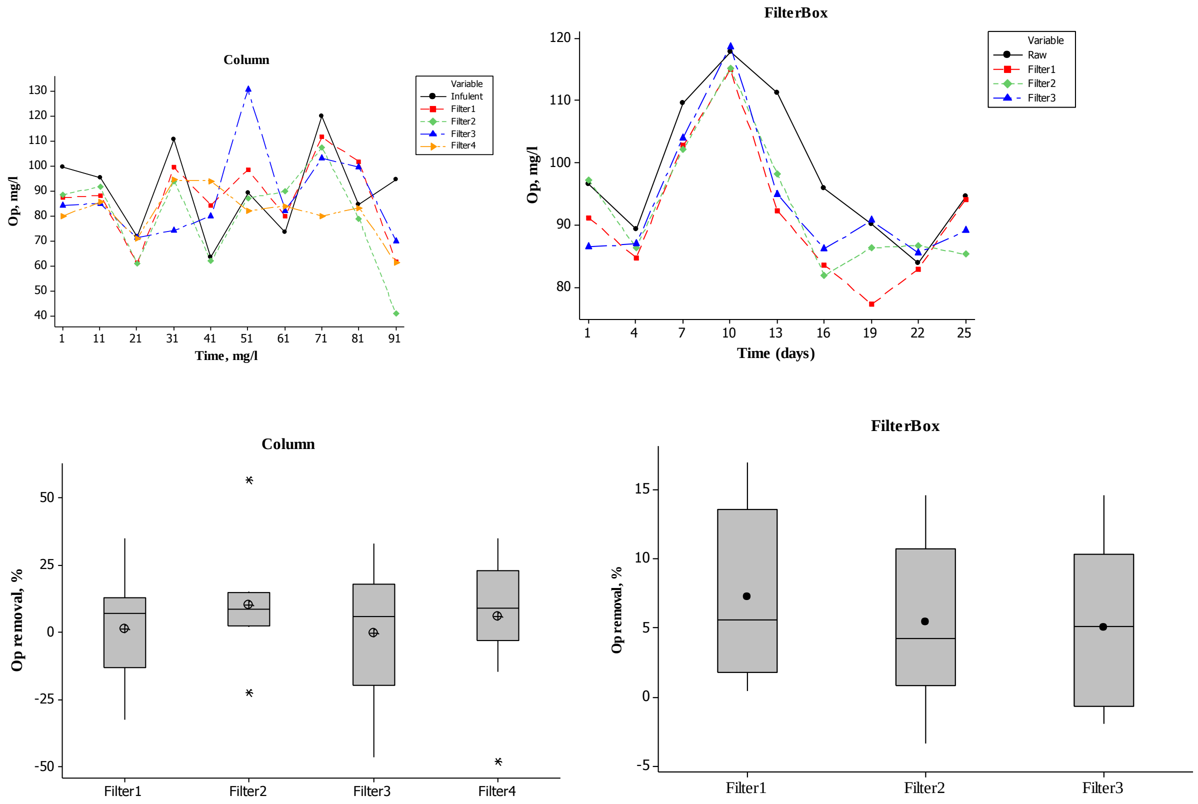


Figure 21. Trend and percentage removal in both experiments

4.3. Filtration capacity (flux)

Due to longer and repeated drying and resting events on the column experiments, it was difficult to draw consistent infiltration capacities of the textile filters. Thus, the result in (Fig22) presents the infiltration capacities as it is measured on the FilterBox experiment. However, in general, filtration capacities on the columns react and regain better filtration capacities after drying events for the initial couples of loadings, and then decrease in the column experiment. Refer to the filter clogging phenomena, *section 5.2* and (Appendix5).

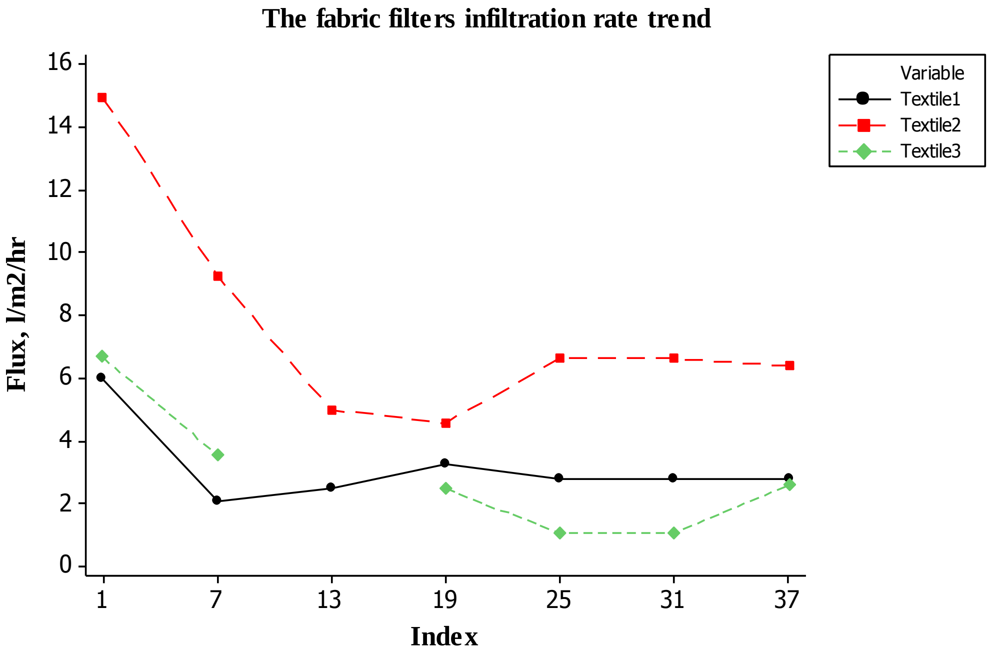


Figure 22. Textile filters filtration capacity trends

The filters have an average infiltration capacity of 3.19, 7.66, and 2.92Lm^{-2}hr^{-1} in textile1, 2 and 3, respectively. Filter3 has a maximum filtration capacity of 15Lm^{-2} hr^{-1} and minimum down to about 4.5lm^{-2} hr^{-1}. Textile2 seems to be steadier compared to the other two filters with an average filtration capacity of 3.19lm^{-2}hr^{-1}.

4.4. Physicochemical changes inside the column experiments

4.4.1. pH vs height inside the columns

Generally, the average temperature and pH relative to height drop inside the column doesn't show much variation compared between inside column measurements and relative to the influent. Relative lower pH range was measured in both the upper and bottom parts of the columns, unlike the middle part (Fig23). More or less similar pH ranges (6.7-7.1) can be seen both in C1& 2 relative to C3, (6.7-7.7). However, these are found to be within the overall pH range of the influent (Fig13). Comparatively, the bottom layer of the columns could be characterized as much thicker sludge than the middle up to the top scum cover (Fig24) because relatively higher pH was measured.

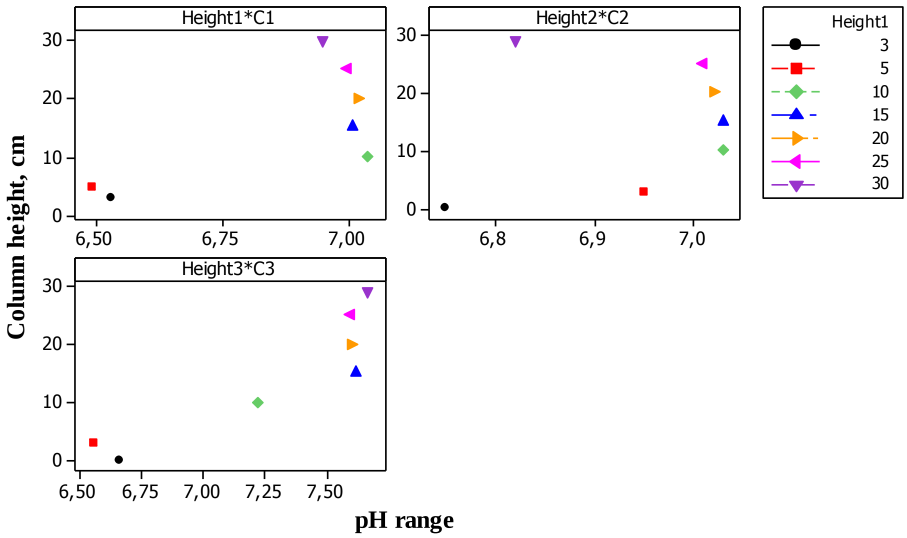
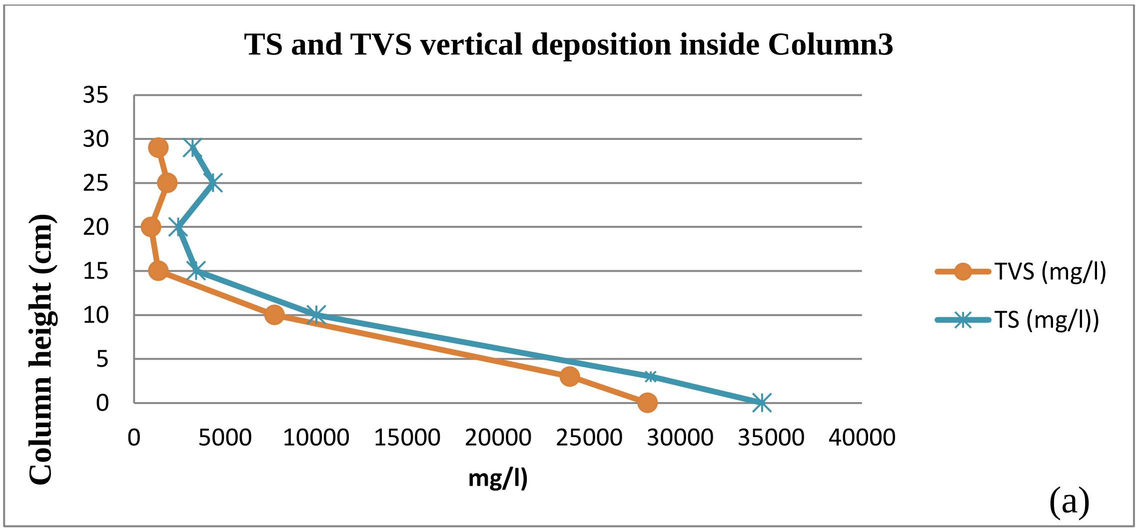


Figure 23. pH VS height inside the accumulated column sludge

4.4.2. Waste deposition patterns inside columns

Both the TS and TVS deposition inside the columns appeared to follow similar trends. Higher amount of TS and organic matter were relatively deposited at the bottom and upper scum layer. This indirectly indicates that the impact it will have on the side filtration in the FilterBox, as the surface to side filtration will characterize with relatively high content of wastes and easily drain, since it is less covered with retained sludge relative to the bottom surface.



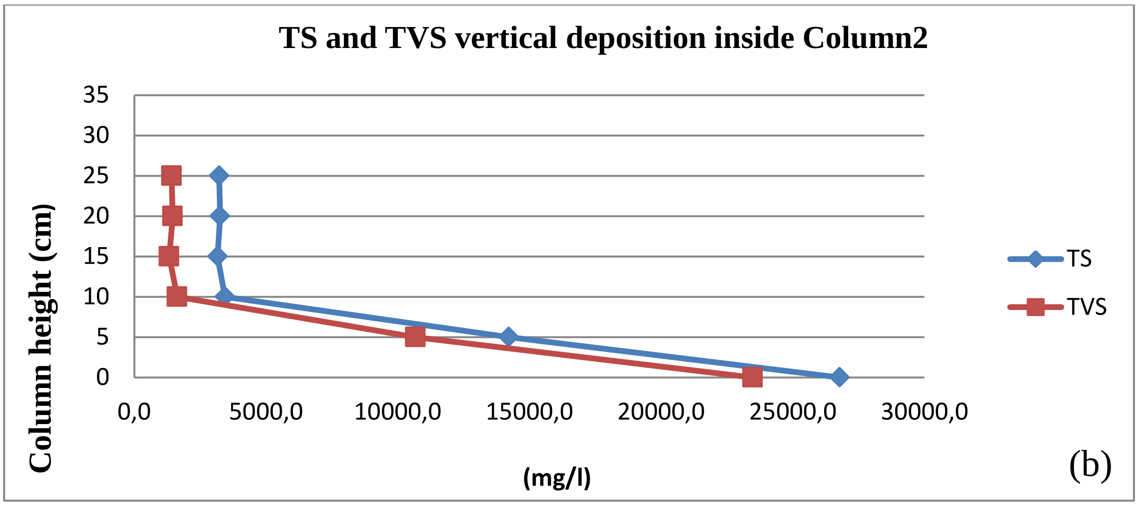


Figure 24. Waste depositions inside the columns

Chapter 5

Discussions and Perspectives

5.1. Filterable Removal: *implications, kinetics and optimization*

One evident way to reduce media clogging is to remove the influent particulate matter (García, Rousseau et al. 2007). This is because most of the contaminants in wastewater residues are associated with those solid particulates (Cheremisinoff 2002; Chavez, Jimenez et al. 2004). This association could probably be higher with black wastewater influents as it is characterized with higher suspended content as discussed and summarized earlier in the result *section 4.2.2* and the theory part, *section 2.4.1*. Therefore, effective filterable particulate removal as pretreatment can leave behind only those contaminants that are dissolved or associated with colloidal matter. Thses are easier for microbial biodegradation in biological treatments without further intensive hydrolysis (Levinel, Tchobanoglous et al. 1991) and effect of direct pore physical plugging (Winter and Goetz 2003) as discussed in *section 5.1.1* below.

5.1.1. Biodegradation kinetics

Beyond the direct effect on media´s pore volume reduction and plugging, large size particulates in the wastewater directly affect the rate of biodegradation by microorganisms (Fig25). Hence, Optimal oxygen, temperature and microorganisms are the most basics in biological wastewater treatment (Dimock and Morgenroth 2006). Organic compounds commonly contain elements of (COHNS) with smaller molecules that can be easily metabolized without further hydrolysis microorganisms which increase rate of waste assimilation and mineralization (Levinel, Tchobanoglous et al. 1991). Because, those large suspended solids, colloids and macromolecules need to be reduced by hydrolysis into smaller molecules before they can be metabolized and assimilated.

The influence of particulate size on hydrolysis rate has similar effect on the surface area requirements for biodegradation and mineralization, mainly the clog matter. Hence, smaller particles, obviously with higher specific surface area than larger particles, are hydrolyzed faster than the bigger ones (Dimock and Morgenroth 2006). Hydrolysis results in both release of readily biodegradable substrate and breakup of larger aggregates resulting in an increased specific surface area available for hydrolysis which ranges from approximately 2 to 3 days to takes place (Dimock and Morgenroth 2006).

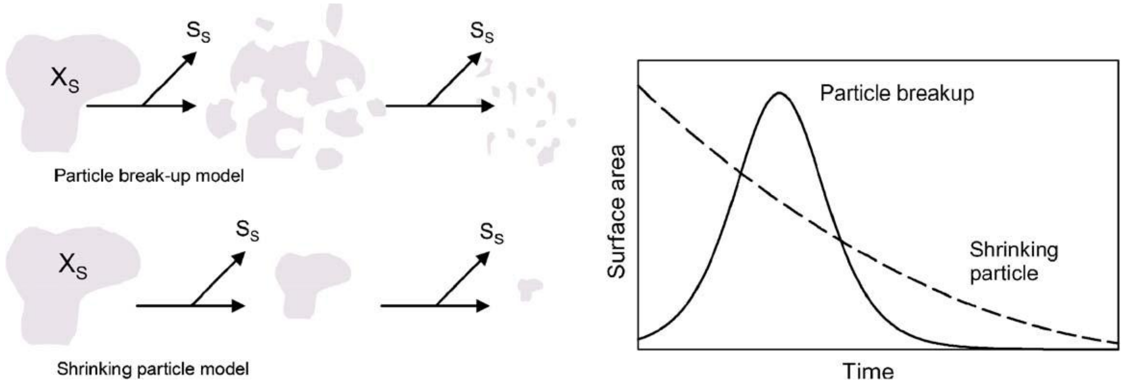


Figure 25. Conceptual comparison of surface based kinetics with and without particle breakup.

Source: (Dimock and Morgenroth 2006).

This plays an important factor in optimization onsite treatments, as the bigger sized particulates need more time for biochemical reductions. Besides, the longer time it took for particulate degradations, the larger areal space will obviously need, or reduce loading rates to avoid clogging on the media. Thus, the treatment plat either needs larger area or faces the clog problem.

Moreover, Müller and Lützner (1999) in (Winter and Goetz 2003) point out that elevated organic loads can cause oxygen deficits and increase organic matter accumulations in the filter bed as a result of which decreases the pore space. That is the reason why intermittent/discontinuous loading and resting to a clogged media is suggested to expose the clog matter to oxygen and be mineralized (Heistad, Paruch et al. 2006). Another reason why the organic matter and rate of biodegradation are interdependent can be seen in the oxygen consumption during the five-day standard test period for $BOD_{5.}$

Therefore, filtering the inlet wastewater and reducing the large particles prior to the microorganism or filter media could potentially enhance the treatment efficiency and rate of biodegradation. The implication is that it enhances rate of clog mineralization and system service longevity. The process in biological treatment kinetics can be summarized in three stages as:

Oxidation

COHNS + O2 +bacteria $\longrightarrow$ CO_2 +H_20 +NH_3 + products+ energy

1. **Synthesis:**

COHNS + O_2 +bacteria + energy $\longrightarrow$ $C_5H_7NO_2$ (new cell)

2. **Endogenous respiration:** which is OM mineralization and stabilization

$$C_5H_7NO_2 \ + 5O2 \ \longrightarrow 5O_2 \ + NH3 \ + 2H20$$

5.1.2. Does removal of filterable content mean Nutrient and pathogen removal?

As it is highlighted in *section 1.2*, there are clear relationships between the concentration in the inlet and subsequent effects on filter media performance, particularly to larger particulate sizes. Similarly, the rate of nutrient removal also depends on the inlet concentrations. Adam, Krogstad et al. (2005), studied rate of P saturation using a Filtralite® media in a box experiment and found out that boxes loaded with high inlet P concentrations (15ppm) at loading rate of (2.5-5Lday^{-1}) reached 90% saturation after 150days of operation, while boxes loaded at lower rate 1.25Lday^{-1} reached 70-99% saturation in 1.5 years. Moreover, the study highlights that the higher existence and rate of saturation in the inlet vicinity relative to the outlet can show that some of the nutrient could be attached to bigger particulates, which normally are retained in the inlet in most cases (Zhao, Zhu et al. 2009). Filter medium, loaded with higher concentrations also saturated much faster than the ones loaded with lower inlet concentrations (Adam, Krogstad et al. 2005; Adam, Krogstad et al. 2007a).

Another interesting study by Chavez, Jimenez et al. (2004) showed that, on the relation of sizes and pathogen, removal of a given waste water can be estimated using the amount of particulate and sizes. The study clearly puts a model to estimate, for example, Helminth ova as:

*Helminth ova (ova/L)= 0.5(volume of particles 20-80*µm*, ml/m*^{3}*);* $R^2=0.98$.

The above model, which indicates 98% of the Helminth ove, can be determined using the model with some precondition specifications. The study also concludes that by removing all the particulates larger than 20µm, all the Heminth ova, 43% of COD, 60% ammonia nitrogen and 10% phosphorus can be removed. This prediction actually is in line with the study for the COD and phosphorus removal, particularly Tp.

The modeling size range (20-80µm) is actually smaller than the textiles pore opening used in this study (i.e. 100µm in textile1 & 70µm in textile3 and much larger in textile2). However, since most of the filtration were governed and takes place above the accumulated sludge, the textiles pore opening might bring them into the range of the modeling size or might not. More importantly, by removing these larger particulates, there is a possibility of removing substantial amount of pathogens, and to greater extent, OM to optimize preceded treatment process.

5.1.3. Optimization OWTS

The strategies for optimization of onsite treatment technologies may depend on local environmental factors. However, some of the general approaches could possibly be common for OWTS optimizing and sustainability. The possible strategies for performance optimization, especially issues related to cogging are discussed and summarized on the clog management *section2.5.5.* But optimization of OWTS may not restrict only to higher hydraulic loading or size reductions. Optimization of a given system could possibly include the following issues at maximum possible:

- Longer functional service time (service longevity)
- Lower O&M costs, with possibly lower capital costs
- Higher loading rate by reducing clogging and hydraulic problems
- Reduced footprint
- Uses locally adaptable and sustainable technologies with low energy uses

Therefore, looking particularly in this case study, by incorporating these textile filters or others as pretreatment stage, much of the particulate matter can easily be retained on the filters.

5.2. Filter clogging physical characterization

Column experiment

Particulate matter accumulation on the filters started within the first 10min after wastewater application in all the columns (Appendix5.1a). This can easily differentiated comparing both (Appendix5.1b vs a) before and after loading, which corresponds to (Fig26a). The accumulation can be visible with a naked eye easily in (Appendix5.2), which could correspond to (Fig26b). Since C_2 is characterized by bigger pore opening relative to the others (C1, C3 and C4) it can be observed with little initial sludge retain compared to the others.

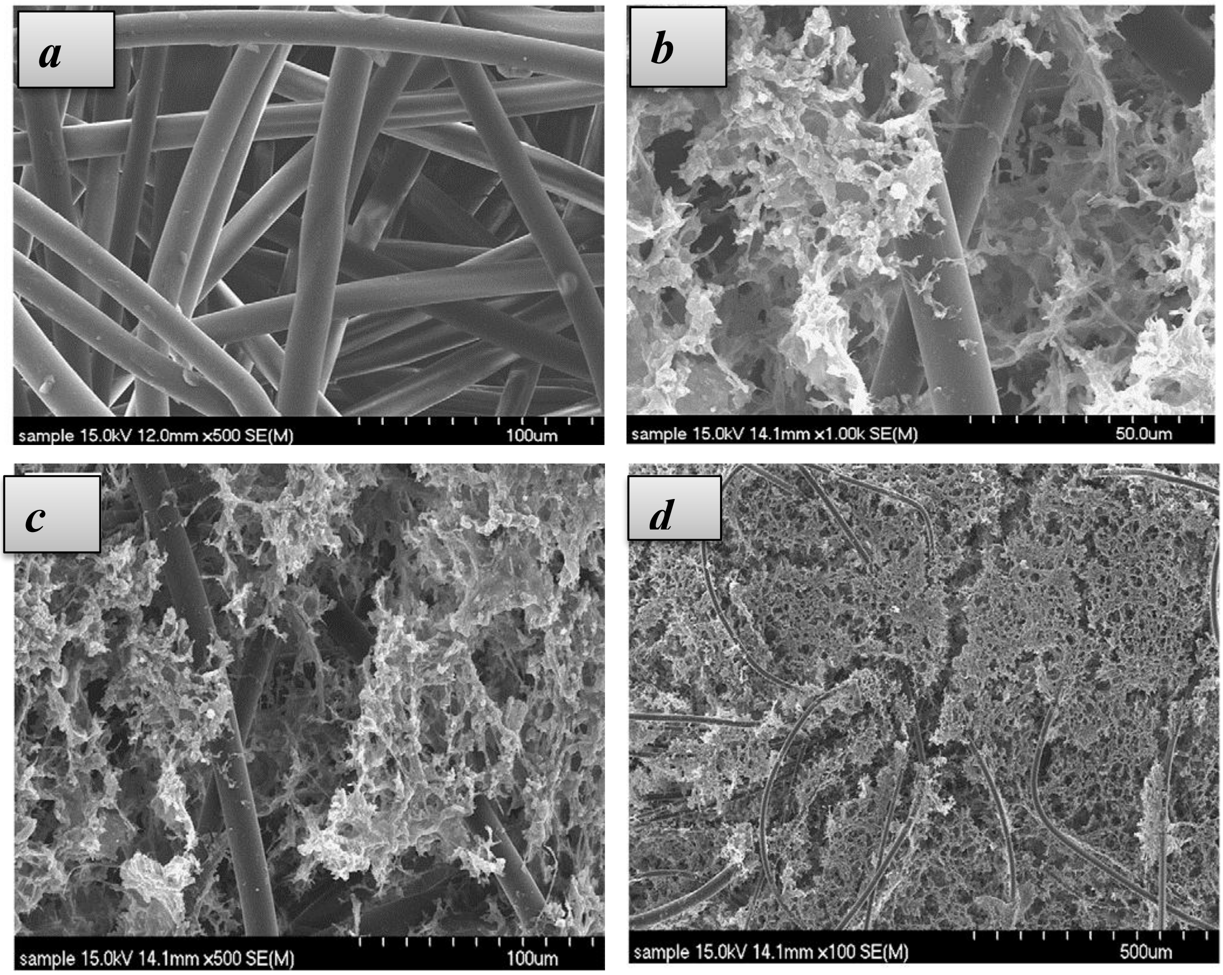


Figure 26. Typical clogging development in a nonwoven textile filters

Source: (Ren, Shon et al. 2010)

Similar studies by Seo, Moon et al. (2003) reported activated sludge cake layer formation on the surface of a nonwoven fabric filter during 20min of operation. The daily loading operations continued for about four weeks with signs of clogging and ponding, that the wastewater starts to float above the developed cake sludge but still not hydraulically clogged. Fabric filters were then subjected for four weeks drying/resting period to gain insights of the fabric reactions both to clogging and hydraulic regenerating. After the resting period, sludge cake were totally dried, cracked and detached from the sidewalls of the pvs column (Appendix5.1c). Hydraulic were regenerated, but, waste removal quality were decreased compared to the results sampled before the resting period and results after the first operational load.

This operation continued for almost three months with some intermediate resting/drying in between. Clog developed to a larger scale and decreased in hydraulic performance and wastewater floated for days to weeks but still with much reduced hydraulic (Appendix5.1d).

Studies by Ren, Shon et al. (2010) estimate such biomass cake to comprise 47.7% carbon, 15.5% nitrogen, and 31.8% oxygen, for a total of 95% of the overall mass retained on the filters. The amount of retained biomass and pattern of accumulation in this study can be seen in (Fig28).

FilterBox Experiment

Generally, the FilterBox experiment was not clogged to this study termination. Some ponding tendencies were observed towards the experimental end (Appendix5.2e). The FilterBox experiment was characterized as having less clogging tendency over the column experiment probably because of the intermediate loading and surface to side filtration (pointed with arrows in Appendix5.2e) unlike to the column, which was only one side filtration from the bottom surface. Summery on the process of clog development on the FilterBox experiment can be found in (appendix5.2).

5.3. Direct effluent filtration as pretreatment

Physico-mechanical pretreatment based on the separation of mainly suspended particles from wastewater in the first process step is an advantage. Because, majority of the wastewater constituents are found in particulate form or associations of particulates (Levine, Tchobanoglous et al. 1985). In this study, the influent COD concentrations median of 11101mgl^{-1} was reduced to about 55% in the FilterBox, and up to 65% on the column experiment was achieved (Fig18c&d). Similarly, median of about 20-60% TS and about 70% TSS were reduced, leaving behind less concentrated effluents as can be seen in Fig27, the retained sludge vs drained effluent.

Figure 27. Retained sludge vs drained effluent

Similar studies by Murat Hocaoglu, Insel et al. (2010), on measurements on several influents showed that upto 70% of COD is related to particles bigger than 0.45μm and many pollutants are incorporated into or adsorbed onto particulate material (e.g. nitrogen, phosphorus, heavy metals, organic micro-pollutants and pathogens). Chavez, Jimenez et al. (2004) also suggests over 90% of the suspended material and up to 70% of the sources of turbidity in wastewater are caused by particulate matter sized between 20-80µm that can be retained with proper pretreatment like the textile filters used in this study with further advancements. A similar conclusion by Levine, Tchobanoglous et al. (1985) concluded that most of the TSS, COD and organic wastes are accumulated near surface of filter mediums than towards to the out late that promotes clogging at the surface than deep in the outlet. Therefore, a pretreatment that can retain those suspend particulate matter can enhance its performance and sustainability.

5.4. The textiles ranking

Prizing a single filter over the others is rather difficult as the filters have their own distinct properties over one another. Besides, variability in resting and loadings seemed to affect the filters equally though the filters have variable pore opening. Hence, the accumulated sludge (internal filtration) seems to play greater role than the pore openings. For example, textile2 which can be characterized as having considerable pore opening over the other two filters and the fourth filter filled with organic media appear to perform in similar ranges. Textile2 has also a higher flux over the other two filters but performs in a wider range and has direct response to initial loadings and loading after resting events, which means it fluctuates very much with situations.

5.5. Opportunities and Possibilities

Development on more efficient pretreatment to optimize onsite treatments and soil application was quite a long interest (Siegrist, Tyler et al. 2000). Recent studies, for example (Heistad, Paruch et al. 2006) introduce a compact up-flow bio-filter pretreatment unites aiming to enhance removal efficiency while reducing the filter volume for subsurface CWs, to avoid both cost and space requirements. Studies in the Nordic systems also anticipate less footprint treatment plants can replace bigger constructed wetlands with similar qualities preceded with better pretreatment steps (Jenssen, Krogstad et al. 2010). However, problems related to medium clogging and O&M costs pose a threat as discussed earlier. All these show that shows with a better pretreatment, there is high potential that the systems could made available in more compact and efficient way to end users. This not only could reduce the volume and costs of the treatment plant but also could enhance applications with problematic soils. For example, incorporating a direct influent pretreatment on the developed biofilters might enhance the performances for the reasons discussed in sections *5.1.1-5.1.3, 4.1.6 and 1.2.*

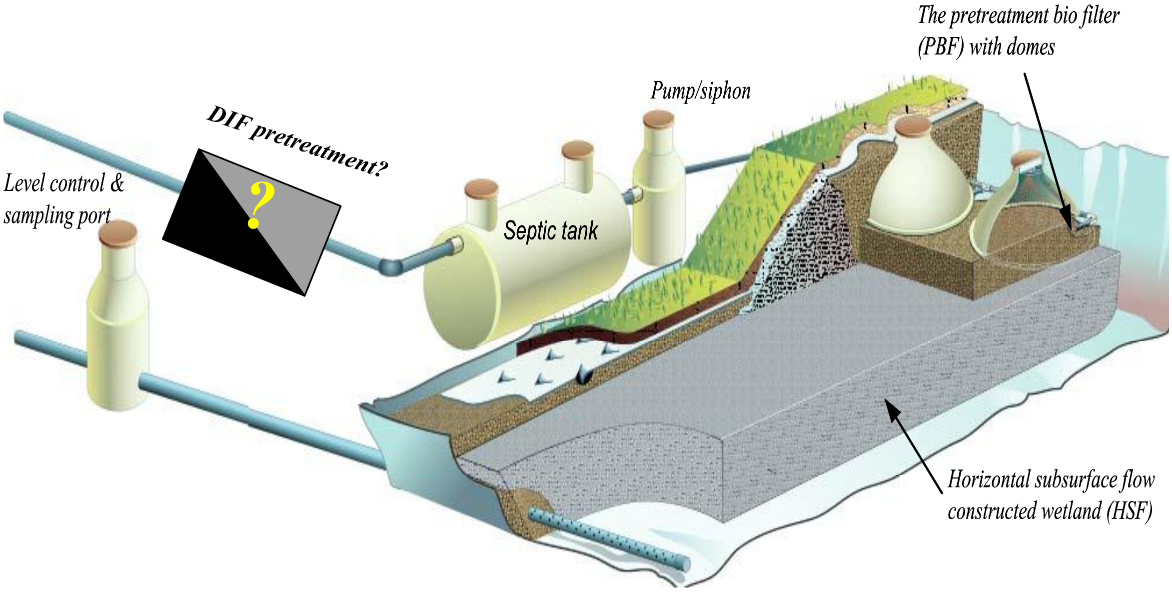


Figure 28. Possibly direct influent pretreatment marked (?) to a compact biofilter treatment

Source: (Heistad, Paruch et al. 2006)

5.6. Strengths and weakness of the study

Being carried out in the Students' dormitory of the University, the experiment could represent various feeding, drinking, cultural and behavior variations in toilet use and wastewater factions (Meinzinger and Oldenburg 2009a). The auto simulated mixing and loading rates could also enhance the data quality and help to monitor easily when fitters are clogged and the loading dates can postponed. Following all the basic standards for sample analysis and analyzing immediately after collection are all an advantage for the data quality.

On the other hand, since the black wastewater source was pupped a considerable distance connected by pipeline, there might be changes in content, especially to the nutrient contents. Conducting this experiment during a summer time might also have contributed to high rate of decompositions due to warmer temperature that might result in higher phosphorus release and an increase in the rate of organic matter degradation by implication clogging rates. Moreover higher loading rate at the first phase and shorter time in experimental tests in the second phase might reduce the strength of drawing conclusions from this study. There were also some shortages of influent sources from the holding tank because of students' summer vacation, which sometimes postponed the sampling date.

Chapter 6

Conclusion and Recommendation

6.1. Conclusion

From this study, the following conclusions can be drawn;

Waste removal performance:

- The textiles has a median removal potential of about 55% -65% COD, 35-45% TS, 60-70% TSS, 50-65% TVS and around 20-25% Tp from inlet to outlet. There were no evident differences for Op removal between the influent and effluent, except about 5% removal mainly in FilterBox experiment. Average removal of 41.5%, 38.9% and 41.16% in textile1, 2 and 3 was measure for BOD5 on the FilterBox experiment.

The clog regulates the infiltration:

- The loading pattern, resting and drying events, seemed to affect the filters performance equally. Thus, it seemed quite logical that the developed sludge regulates the infiltration performance than the individual textile properties, at least in this study. As textile2, which has much larger pore opening than the other two textiles perform similarly with minor variations even better performance especially to flux.

Loading and application patterns:

- The columns which basically loaded with continuous pattern, except during the resting/drying periods experience clogging within shorter period compared to the FilterBox experiment, loaded on discontinuous base. Thus seems intermittent loading and side filtration plays an advantage in the FilterBox experiment.

Hydraulic:

- The filters have an average infiltration capacity of 3.19, 7.66, and 2.92$Lm^{-2}hr^{-1}$ in textile1, 2 and 3 respectively as measured from the FilterBox experiment.
- Periodic resting regenerates the textiles hydraulic capacity but seem to increase contaminate passage, compared to the results sampled before the resting period and after the first operational load.

6.2. Recommendations

- In situations where the textile filters are supposed to be used in situation where occasionally and seasonally used areas; the developed clog above the filters will be dried and cracked. Therefore, prior flushing with pure water to make the cracked clog wet and close the opening is advisable to avoid direct passage of raw waste.

- The location of the influent inlet to the textile filters should be modified; as dropping from that height disturbs the retained and settled sludge which might increase wastewater constituents passage both from side and bottom filtrations. This can be done by making the inlet slanted at the inlet opening.

6.3. Areas for further studies

Optimal OM for biofilm development:

- It is known that biofilm growth will enhance treatment quality for the system. Microorganisms depend on the available food in the inflow for this function. As the same time it is blamed for treatments malfunction as a result of media clogging, infiltration rate reduction and ponding. So, to what extent should be the OM in the influent removed without halting the biofilm development.
- Further studies to integrate the textile filters to biofilter and study how that affects the rate of degradation and pathogen removal capacity, due to reduce amount OM sources and its effect on the biofilm growth.

Keeping OWTS self-cost sustainable:

- Identify possibilities and mechanisms that OWTS can generate income by providing raw sludge for biogas and fertilization producing individual companies or at least emptying the sludge for free in exchange of the produced waste.

Chapter7

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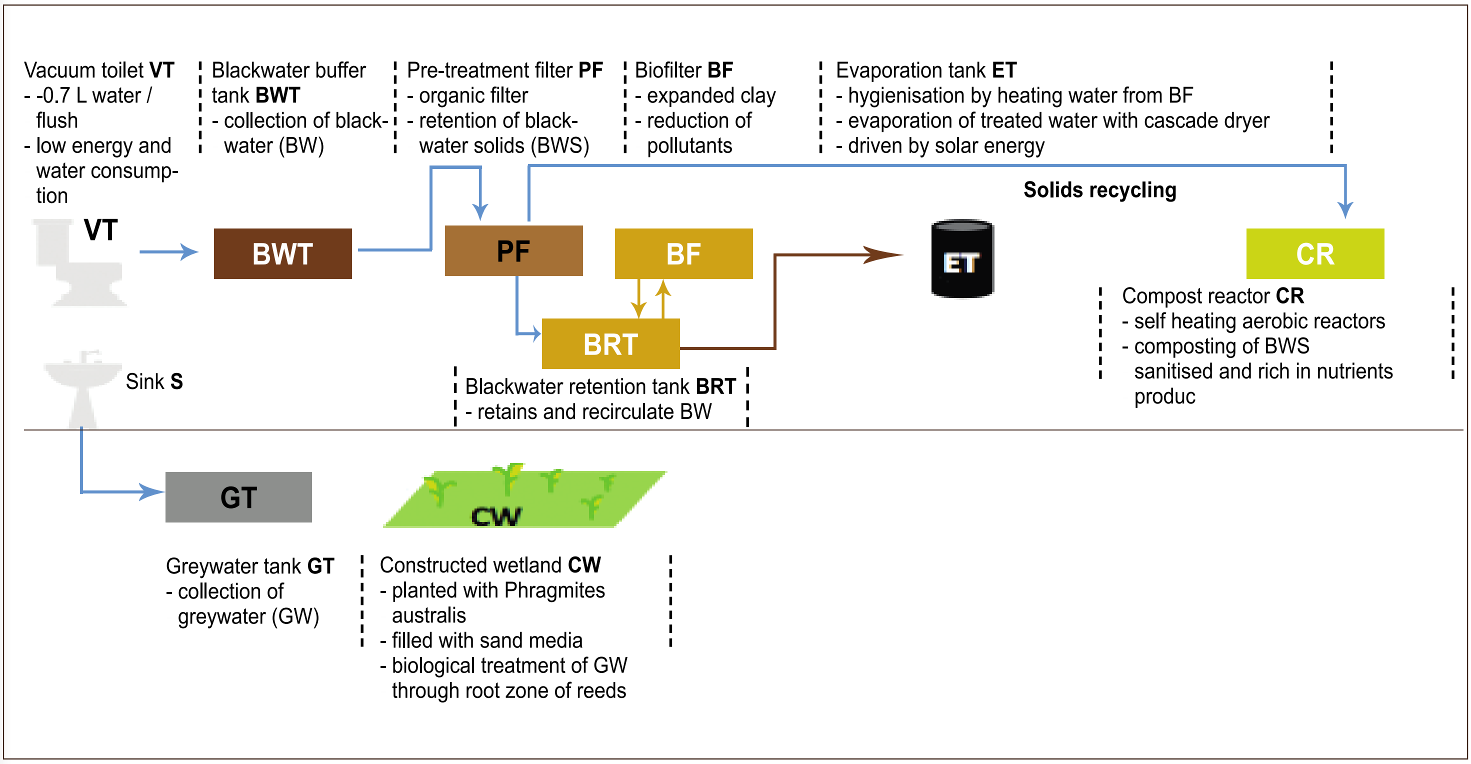
Chapter8

Appendix

1. Holistic approach of the treatment systems



Source: Sanbox research project (http://www.sanbox.info)

2. FilterBox Experimental setup overview

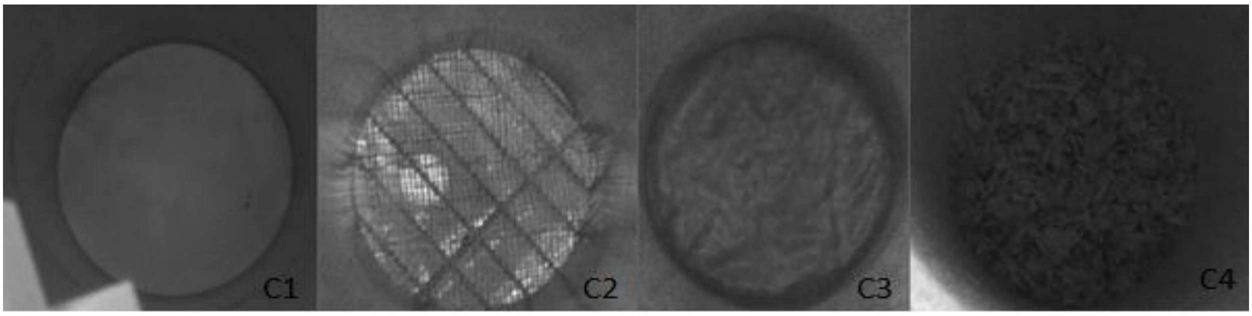
3. The textiles property

Parameters	Textile1	Textile2	Textile3
Pore opening (μm)	100(+/-30)	NA	70(+/-21)
Tensile strength (kN/m)	11.2(-1.1)	NA	29(-2.9)
Thickness(mm)	1.3(+/-0.26)	NA	2.4(+/-0.48)
Weight (gm^{-2})	135	NA	355
Durability in, 4<pH<9 & temperature <25°C, years	25	NA	25
Composition	100% polypropylene	NA	100% polypropylene

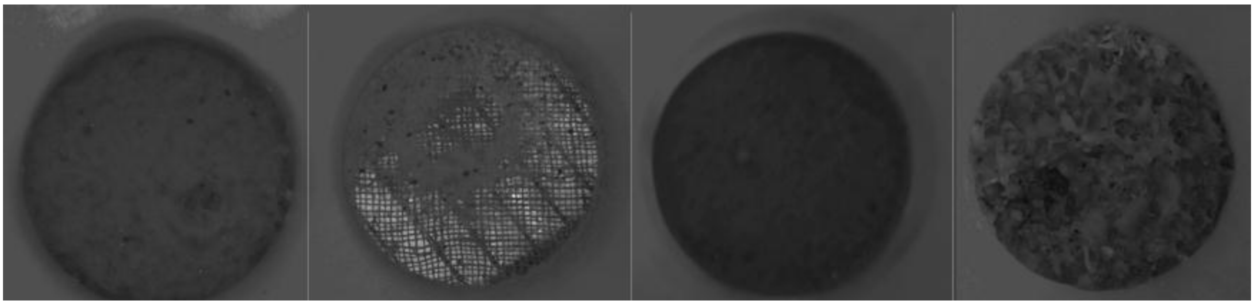
4. Lab analysis overviews

5. Clog development trends

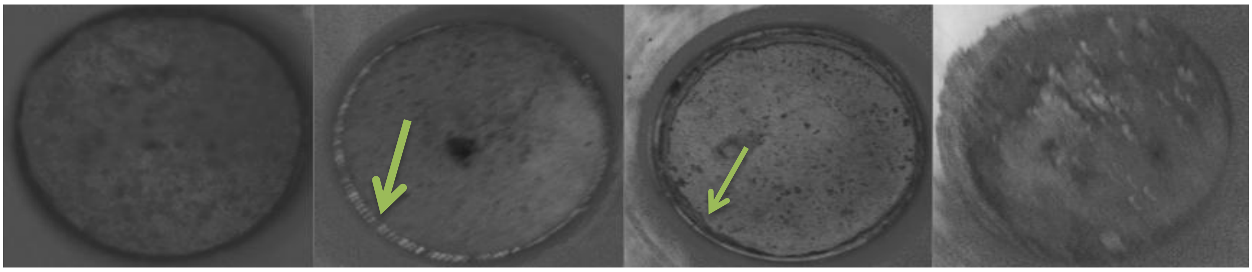
5.1. Clog development in columns



***a**. Textile filters before loading*



***b.** Textile filters in the second load,*



***c**. Sludge dried and formed a cake shape and detached from the pvc wall (after four weeks drying period)*
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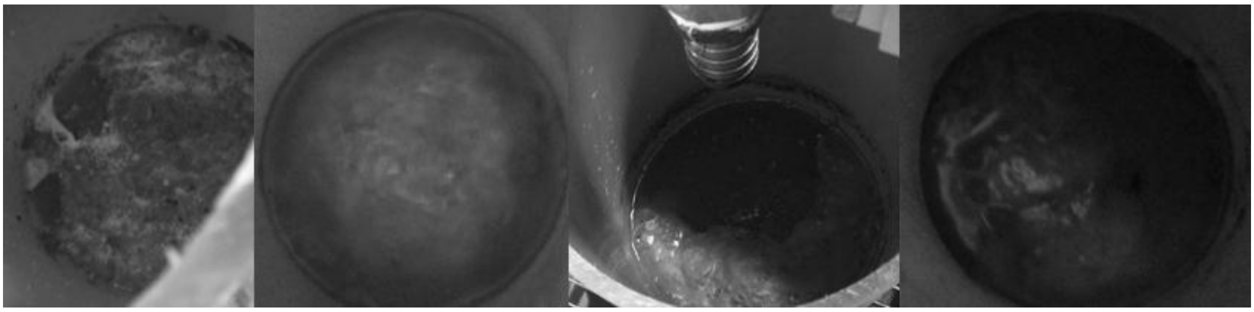

***d**. Clogging development after the drying period, this sustains for the filters toward the experiment end. Filtration slow dowun to 3-7 days and scum coverd at the top.*

***f**. Vertical extraction inside columns: as it can be seen from the pictures; most of the particulate matter was deposited toward the bottom (right side) and at the most top as floating scum (right side). The middle one is more of water and has less particulate*

5.2.Clog development in FilterBox

a. Initial loading (both filter1 &3 retain much OM from the very beginning)

b. Third load

c. Around mid of the experimental period

d. Towards the end experimental stages

e. Towards the end of the experiment (it started to pond and as it is indicated by the arrows