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Greywater treatment using aquatic filtration for possible reuse in landscape irrigation

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GREYWATER TREATMENT USING AQUATIC FILTRATION FOR POSSIBLE REUSE IN LANDSCAPE IRRIGATION

By

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ABSTRACT

Fresh water scarcity continues to present itself as an underlying global problem as we steadily approach 2025 (UN 2006). Egypt is no exception to the rule, facing several water pollution problems extending from all sectors in the country and negatively affecting water quality and public health. According to the Ministry of Water resources and irrigation (1997), the average water uses in the Egyptian household comprises 18% for shower and bath, 18% for toilet flushing, 8% for laundry, 14% for dishwashing and drinking, 10% for cooking, 30% for irrigation and 2% for other activities which makes onsite treatment and reuse of greywater an attractive option to bridge the gap between water demand and supply in Egypt and help build biophilia settlements that are ecological and sustainable.

The main research aim of this work was to study the potential of water hyacinth for removal of organic pollutants and pathogens from residential greywater using aquatic filtration pilot scale system in order to yield water suitable for irrigation of residential lawns.

The different experiments of the current work were conducted in five phases at the facilities of the American University in Cairo (AUC). In Phase I, synthetic greywater was formulated in the lab to run the different experiments of the study by mixing tab water with different chemicals that simulate the different contaminants commonly present in greywater and it was observed that the water quality parameters of the synthetic greywater stimulated in the current study were within the range of the values of water quality parameters reported in literature for light and heavy greywater.

In Phase II, water hyacinth, papyrus reed and common reed were used to investigate the effectiveness of treating synthetic greywater compared to a control (no plant condition). It was found that over the period of 19 days, water hyacinth was able to remove a total mass of 83 mg TDS (45% higher than the control sample), 0.5 mg PO_4- (60% higher than the control sample), 53 mg COD (5.7% higher than the control sample) and 572

mg FC (44% higher than the control sample) and was able to achieve the lowest greywater normalized evaporation rate with a total of 0.114 liter of water per kg of plant wet mass per day (l/kg.d). Common reed was found most effective in treating organic and suspended pollutants, compared to water hyacinth and papyrus reed. However, the planting cost, removal operation and overall management is considered favorable to water hyacinth over the other two plant species.

In Phase III, the effect of different hydraulic loading rates on the treatment performance of synthetic greywater was investigated using similar wet densities of water hyacinth. it was observed that 20 days of experiment, water hyacinth in Reactor 5 (HLR = 0.29 $m^3/m^2/d$) was able to reduce the turbidity, TSS, COD and BOD_5 of greywater from 176 NTU to 14 NTU+7 NTU, 294 mg/l to 20 mg/l+13.5 mg/l, 176 mg/l to 16 mg/l+12 mg/l and 102 mg/l to 7 mg/l+6 mg/l (on average basis), respectively. It was also observed that the operation of the treatment system at HLR of 0.29 $m^3/m^2/d$ results in an effluent organic quality (BOD_5 and COD) that complies with the limits reported in the Egyptian Code of Practice for Reuse in Irrigation; Category A (501-2015). Reactor 5 (HLR = 0.29 $m^3/m^2/d$) was also able to withstand hydraulic shock loading with a turbidity removal rate of 68.4%, TSS removal rate of 54.1%, COD removal rate of 39.8% for the first four hours and a removal efficiency of 86.8%, 63.9% and 80.6%, respectively for the next twenty hours.

In Phase IV, the effect of different wet densities of water hyacinth on the treatment of synthetic greywater was investigated using similar hydraulic loading rates. It was observed from the experiment that lasted 20 days that water hyacinth in Reactor 5 (Wet density = 4.345 kg/m^2) was able to reduce the turbidity, TSS, COD and BOD_5 of greywater from 28 NTU to 7 NTU+3.3, 20 mg/l to 4 mg/l+1.7 mg/l, 54 mg/l to 16 mg/l+4.1 mg/l and 37 mg/l to 10 mg/l+2.8 mg/l (on average basis), respectively. Water hyacinth in Reactor 4 (Wet density = 2.173 kg/m^2) was also able to reduce the turbidity and TSS of greywater from an average of 28 NTU to 10 NTU+3.7 and from 20 mg/l to 5.5 mg/l+2.9 mg/l, respectively.

In Phase V, the performance of the aquatic filtration system in treating real greywater when using the optimum operating conditions obtained from Phase III and Phase IV was investigated. The greywater treatment system which operated for a period of 29 days at HLR (0.29 $m^3/m^2/d$) and highest wet plant density (2.173 kg/m^2) was able to reduce the turbidity, TSS, COD and BOD_5 of greywater from 82 NTU to 54 NTU+20 NTU, 52 mg/l to 34 mg/l+24 mg/l, 366 mg/l to 217 mg/l+71 mg/l and 222 mg/l to 129 mg/l+43 mg/l (on average basis), respectively.

The validation of this synthetic effluent by comparison with real greywater demonstrates that the designed and constructed aquatic filtration system using water hyacinth is a promising, low-cost, low-tech greywater treatment system that can be run and maintained by unskilled operators. However, the improvement in treatment in the Water Hyacinth based system is of particular significance considering the strict effluent quality standards recently imposed by the Egyptian Code for Landscape Irrigation. Hence, future research (including scale economic studies) should be carried out to investigate the use of greywater at the community level with the optimization of different techniques that could further enhance the greywater effluent quality to the permissible level of 1st group (i.e. advanced treated water) as unrestricted water reuse in landscape irrigation according to the ‘‘Egyptian Guideline’’.

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NOMENCLATURE

pH	Potential of hydrogen
TSS	Total suspended solids
TDS	Total dissolved solids
FC	Faecal coliform
DO	Dissolved oxygen
COD	Chemical oxygen demand
BOD_5	Biological oxygen demand
TC	Total carbon
TOC	Total organic carbon
NH_3-N	Ammoniacal nitrogen
NO_3-N	Nitrate nitrogen
PO_4^-	Phosphate
TN	Total nitrogen
TP	Total phosphorus
DI	Deionized water
UV	Ultra violet
HLR	Hydraulic loading rate
OLR	Organic loading rate
ptCo	Platinum-Cobalt scale
NTU	Nephelometric turbidity unit
CFU	Colony forming unit
LGW	Light greywater

HGW	Heavy greywater
ECP:	Egyptian code of practice
AM	Ante meridiem
PM	Post meridiem
STDev.	Standard deviation

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CHAPTER 1: INTRODUCTION

1.1 Background

1.1.1 Sustainable Water Management

Due to the increasing demand on fresh water supply, lack of public awareness about the importance of water conservation in meeting the social and sanitary needs of the present and future generations (World Band, 1995) and the limited capacity of the existing wastewater treatment plants to bridge the gap between supply and demand, source separation has become a feasible option to induce green production, decrease water-borne diseases and upscale social living. The above concept entails the channeling of greywater through the installation of diverter valves followed by the treatment of greywater using innovative low-cost on-site technologies (Diaper and Sharma, 2007), and ultimately the collection, distribution and reuse of treated greywater in firefighting, toilet flushing and landscape irrigation. Wastewater treatment can be divided to two main categories based on location of treatment, method of collection and distribution and integrated processes. In terms of sustainable water management, decentralized systems have prevailed over centralized systems due to several environmental, social and economic benefits. One advantage of treating wastewater onsite is reduced electricity bills, building and operating cost and carbon footprint since centralized wastewater treatment plants often require the use of advanced mechanical and electrical equipment to carry on different physical, chemical and biological treatment processes (USEPA, 2004a). Centralized systems usually necessitate the isolation of the treatment facility from residential settlements as a standard precaution to prevent/decrease the spread of bad odors and health risks associated with possible human interference, which is the reason why they are preferred in highly crowded communities (USEPA, 1998).

On the downside, they are situated in limited space which inhibits the expansion of the facility. Moreover, they require frequent maintenance to accommodate the high number of contaminants present in inlet stream (USEPA, 2008b). On the other hand, decentralized systems deal with smaller rural communities which eliminate the need for skilled technicians and extensive distribution pipes (Wolverton and Wolverton, 2001). They also accommodate cost-effective onsite treatment solutions such as grease and oil trap tanks as possible physical pretreatment units, sedimentation tanks and course filters as suspended solid removal units and septic tanks, bioReactors, ponds and constructed wetlands as possible biological contaminant-removal units. Tertiary units intended for disinfection purposes could also be integrated in such systems (USEPA, 2004). Ultimately, reclaimed water is distributed to nearby households using a system of above or underground short-range pipes to be conveniently used in landscape irrigation and toilet flushing, among another non-potable end uses, or it could be discharged back to surface water (USEPA, 2004).

1.1.2 Greywater Definition

Domestic wastewater mainly consists of two separate streams, one of which is obtained from baths, showers, hand basins, washing machines, dishwashers and kitchen sinks and is widely known as “Greywater”. (Jefferson et al., 1999; Otterpohl et al., 1999; Eriksson et al., 2002; Ottoson and Stenström, 2003). It’s notable that there have been some scientific attempts to further classify greywater based on organic load to light and heavy greywater and that the former, by definition, excludes flows from kitchen, dishwasher and washing machine which is usually contaminated with soiled diapers. (Friedler, 2004). On the other hand, the second stream is obtained from toilet basins which usually contains fecal coliform bodies and is referred to as “Blackwater”. (Ramon et al. 2004).

1.2 Problem Statement

Fresh water scarcity continues to present itself as an underlying global problem as we steadily approach 2025, which is predicted by The United Nations to be the year 48 countries will experience water stress, threatening to change the lives of almost 2.7 billion people around the world as they know it today (UN 2006). Egypt is no exception to the rule, facing several water pollution problems extending from all sectors in the country and negatively affecting water quality and public health. In addition to the growing demand-supply gap driven by the rapidly increasing population and continual steep-up urbanization attempting to better the living standards of the citizens (Arar, 1998). Currently, the Nile River is the main source of fresh water in Egypt, comprising an annual quota of 55.5 billion cubic meters and supplying the agricultural and domestic/industrial sectors with 86% and 14% of fresh water, respectively, as shown in Figure 1. On the alarming side, it is expected that by the year 2025, the annual per capita renewable water will drop to less than 600 m^3, as shown in Table 1, which calls for an immediate collaborative action plan to prevent water pollution, raise public awareness about efficient water saving, and encourage onsite wastewater reuse and recycling.

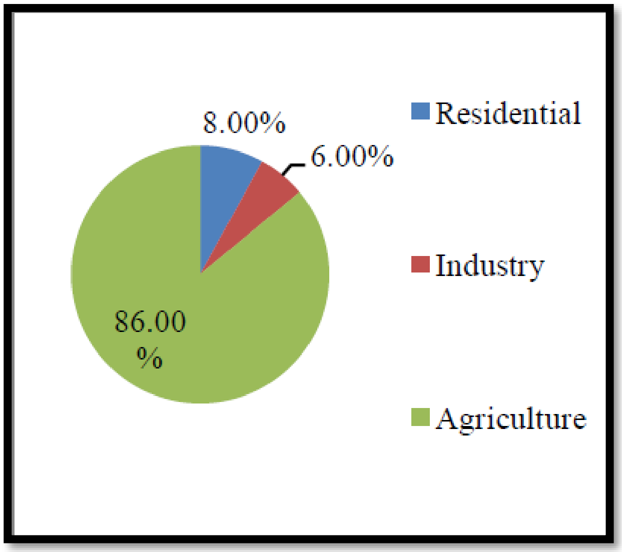

Figure 1: Water Use Allocation in Egypt (Goueli, 2002)

Table 1: Average Individual's Share of Water in Egypt (Bishay, 2010)

Year	**Average Individual's share of water (m^3/year)**	**Change in Individual's share (%) compared to 1947**
1947	2604 (water plentiful)	-
1960	1893	-27.3%
1970	1713 (sufficiency water)	-34.2%
1986	1138	-56.2%
1996	936 (water scarcity)	-64.1%
2003	860	-67%
2025 (expected)	582 (poverty water)	-77.6%

1.3 Objectives

The main research aim is to study the potential of water hyacinth for removal of organic pollutants and pathogens from residential greywater in order to yield water suitable for irrigation of residential lawns.

1.4 Scope of Work

The work presented herein aims to evaluate the feasibility of greywater treatment using aquatic filtration for irrigation purposes. The rest of this section lists the structure of the thesis.

- Chapter 2 reviews the characteristics of greywater, its applications, standards for reuse and different treatment technologies prior to its use for irrigation.

- Chapter 3 demonstrates the experimental set-ups and procedures used to test the performance of different hydraulic loading rates and water hyacinth densities in treating synthetic and real greywater using a collaboration of lab studies and pilot-scale aquatic filtration system.

- Chapter 4 lists and discusses the comprehensive results obtained from the conducted five-phase experiments.

- Chapter 5 summarizes the findings obtained from Chapter 4 and provides recommendations for potential future studies in the field of greywater reuse

CHAPTER 2: LITERATURE REVIEW

2.1 Greywater Characteristics

2.1.1 Quantity of Greywater

According to The Ministry of Water Resources and Irrigation, 8% of the total potable water in Egypt is utilized in the residential areas (Ministry of Water resources and irrigation, 1997). Also, Grey water constitutes 50–80% of the total household wastewater and about 75% of the total municipal wastewater (Eriksson, E. Auffarth, K. Eilersen, A.M. Henze, M. Ledin, 2003). According to the Ministry of Water resources and irrigation (1997), the average water uses in the Egyptian household comprises 18% for shower and bath, 18% for toilet flushing, 8% for laundry, 14% for dishwashing and drinking, 10% for cooking, 30% for irrigation and 2% for other activities. A comparison between different water consumption ratios in other countries (Table 2) also showed that greywater constitutes approximately 54.2%, 52% and 30% of the total household wastewater produced in UK, Germany and USA, respectively.

Table 2: Water Consumption in Various Countries (Jiang; Acheampong; and Bancroft, 2009)

Water Usages	UK (%)	Germany (%)	USA (%)
Toilet	28.2	29	28
Kitchen sink	14.0	---	---
Bath/ Shower/Hand basin	28.2	37	20
Laundry	12.0	15	10
Other (Garden tap, etc.)	17.6	19	42

2.1.2 Quality of Greywater

The far-ranging difference in greywater composition remains to be one of the prevailing challenges in the field of greywater treatment (Al-Jayyousi 2003). This variation could be attributed to many factors such as inlet water quality, daily personal habits, types of detergents used and collection and distribution methods (Eriksson et al., 2002). Many researches have attempted to characterize greywater according to its source, as shown in Table 3. Average values of the physical, chemical and microbiological characteristics of light and heavy greywater from different countries have been summarized in Table 4, Table 5 and Table 6.

Table 3: General greywater characteristics according to source (New Mexico State University's Safe Use of Household Greywater Guide, 1994)

Water Source	Characteristics
Automatic clothes washer	Bleach, Foam, High pH, Hot water, Nitrate, Oil and Grease, Oxygen demand, Phosphate, Salinity, Soaps, Sodium, Suspended solids, and Turbidity
Automatic dish washer	Bacteria, Foam, Food particles, High pH, Hot water, Odor, Oil and grease, Organic matter, Oxygen demand, Salinity, Soaps, Suspended solids, and Turbidity
Bath tub and shower	Bacteria, Hair, Hot water, Odor, Oil and grease, Oxygen demand, Soaps, Suspended solids, and Turbidity
Evaporative cooler	Salinity
Sinks, including kitchen	Bacteria, Food particles, Hot water, Odor, Oil and grease, Organic matter, Oxygen demand, Soaps, Suspended solids, and Turbidity

Table 4: Average values of the physical, chemical and microbiological characteristics of light greywater from different countries

Parameter	**Unit**	**Australia** [(1)]	**Taiwan** [(2)]	**Korea** [(3)]	**France** [(4)]	**Germany** [(5)]
		Bath	***Shower***	***Floor Cleaning***	***Bath+Shower***	***Bath+Shower***
PH	-	6.4-8.1	6.5-7.5	7.27	7.58	-
TSS	mg/l	48-120	29	-	125	-
Turbidity	NTU	60-240	43.1	12.6	150	-
COD	mg/l	-	55	-	399	100-633
BOD_5	mg/l	76-200	23	-	240	50-300
Ammonia (NH_3/NH_4^+)	mg/l	<0.1-15	0.146	-	-	-
NO_3-	mg/l	<0.05-0.2	-	-	-	-
PO_4^{-3}	mg/l	-	-	-	-	-
Fecal Coliform	CFU/100 ml	170-3.3e3	-	-	3.42E+05	0.1-10

References: *Boyjoo et al (2013) and the detailed references in Boyjoo's study were (1) Christova-Boal et al. (1996); (2) (Lin et al., 2005); (3) (Kim et al., 2007): (4) (Chaillou et al., 2011); (5) (Nolde, 2000)

Table 5: Average values of the physical, chemical and microbiological characteristics of light greywater from different countries

Parameter	Unit	UK [6]	Spain [7]	Morocco [8]	Oman [9]
		Bath+Shower+ Handbasin	***Bath+Shower +Handbasin***	***Shower***	***Shower+ Handbasin***
PH	-	6.6-7.3	6.8-7.6	7.6	7.1-7.4
TSS	mg/l	29	32.2-44	-	353-505
Turbidity	NTU	35-42	20-38.8	29	133-375
COD	mg/l	86-575	72.7-171	109-122	58-294.3
BOD_5	mg/l	20-166	-	53-59	42.1-130
Ammonia (NH_3/NH_4^+)	mg/l	0.7-1	-	6.6-11.8	-
NO_3-	mg/l	3.9-7.5	-	0	10.2-28.7
PO_4^{-3}	mg/l	0.5-1.3	-	1	-
Fecal Coliform	CFU/100 ml	-	-	1.4e3-2.48e5	>200.5

References: *Boyjoo et al (2013) and the detailed references in Boyjoo's study were (6) (Pidou et al., 2007) and (Winward et al., 2008); (7) (March et al., 2004); (8) (Merz et al., 2007); (9) (Prathapar et al., 2005).

Table 6: Average values of the physical, chemical and microbiological characteristics of heavy greywater from different countries

Parameter	**Unit**	**Australia (1)**	**Japan (2)**	**Korea (3)**	**India (4)**	**Brazil (5)**	**Germany (6)**	**Turkey (7)**	**Jordan (8)**	**Oman (9)**
		Laundry	***Kitchen***	***Kitchen+Shower***	***Mixed***	***Mixed***	***Mixed***	***Mixed***	***Mixed***	***Laundry***
PH	-	-	9.3-10	-	7.3-8.1	-	6.9-8.1	7.1-7.2	6.35	8.3
TSS	mg/l	88-250	105	30-130	12-17.6	120	-	48-54	168	315
Turbidity	NTU	50-210	-	19-84.8	20.6-38.7	254	-	-	-	44
COD	mg/l	-	271	50-400	244-284	646	640	177-277	2568	231.3
BOD_5	mg/l	48-290	477	-	56-100	435	-	90-116	1056	179.9
Ammonia (NH_3/NH_4^+)	mg/l	<0.1-1.9	-	-	-	2.4	-	1.2-1.3	75	-
NO_3-	mg/l	0.1-0.31	-	-	0.5-0.63	0.05	-	0.13-1.3	-	25.8
PO_4^{-3}	mg/l	-	-	-	1.52-3.36	5.6	9.8	-	-	-
Fecal Coliform	CFU/100 ml	110-1.09e3	-	4.00E+03	3.48e4-3.56e4	5.40E+06	7.5e3-2.6e5	3.57e3-1.1e4	3.00E+05	-

References: *Boyjoo et al (2013) and the detailed references in Boyjoo's study were (1) Christova-Boal et al. (1996); (2) (Itayama et al., 2006); (3) (Kim et al., 2009): (4) (Mandal et al., 2011); (5) (Paulo et al., 2009); (6) (Elmitwalli and Otterpohl, 2007); (7) (Scheumann et al., 2007); (8) (Halalsheh et al., 2008); (9) (Prathapar et al., 2005).

Commonly, there are three streams of greywater in a typical household. Their characteristics can be summarized as follows:

- **Bathroom**

  Wastewater originating from the bathroom comprises showers and sinks. It makes up approximately 65% of the total greywater volume produced by a typical household in Egypt (Farouk, 2011). It usually contains personal care products, hair, lint, body fats, some faecal bodies and mildly dangerous bacteria and viruses (Christova-Boal et al., 1996; Howard et al., 2005).

- **Laundry**

  Wastewater originating from the laundry makes up approximately 25% of the total greywater volume produced by a typical household in Egypt (Farouk, 2011).According to Smulders (2002), it usually contains lint, bleaching agents, foam, oil, grease and chemical detergents which, in turn, comprise a high percentage of xenobiotic organic compounds and non-volatile salts (Eriksson et al., 2003).Moreover, laundry greywater might contain faecal bodies and mildly dangerous bacteria and viruses, resulting from soiled napkins wash.

- **Kitchen**

  Wastewater originating from the laundry makes up approximately 10% of the total greywater volume produced by a typical household in Egypt (Farouk, 2011). It usually contains cleaning agents, foam, food particles, cooking oil and grease which can infiltrate into the soil and decrease its efficiency to receive irrigation water (Jeppesen & Solley 1994). It's worth mentioning that the rather difficult-to-breakdown constituents of kitchen greywater have propelled researchers to rule it out from the main greywater stream (Prillwitz & Farwell 1995; Emmerson 1998; Allen & Pezzaniti 2001).

2.1.3 Applications

Reuse/recycling of domestic light greywater is being adopted all over the world as an emerging eco-friendly and economically feasible mean of water conservation. It is most commonly used in toilet flushing and landscape subsurface irrigation, saving approximately 20% and 33% of the total household water consumption, respectively (Karpiscak et al., 1990). Other end uses can be commercially utilized in unit cooling, firefighting, and industrial washing.

2.1.4 Benefits

Reuse/recycling of treated domestic greywater has proven itself to be a viable option over the past few years, both economically and ecologically. Not only does it recharge ground water, induce nutrients in the soil, stimulate plant growth and ultimately food production, but it also reduces strain on sewage treatment facilities and all in all, minimizes energy consumption and greenhouse gas emissions (Friedler and Hadari, 2006).

2.1.5 Risk Assessment Guidelines

Despite the fact that, up until this day, there remain some unresolved safety issues surrounding the subject of greywater reuse in certain applications, there have been successful attempts by some of the renowned researches in the field to study the effect of reclaimed greywater on the environment and human health, as well as the effect of irrigation method on the transmission of disease-causing agents (Eriksson et al., 2003).For instance, some researchers were able to attribute risks associated with greywater to some chemical factors such as high salinity, excessive alkalinity, high levels of sodium, zinc, and aluminum, high SAR values and other biological factors such as the presence of pathogens, heavy metals, and organic compounds, all of which is dependent on soil type, crop type, greywater composition, loading rate and plant uptake (Roesner et al. 1994, Ottosson 2003, Christova-Boal et al. 1996). Further scientific research was able to highlight enterotoxigenic E. coli, Salmonella, Shigella, Legionella, and enteric viruses as the most common pathogen organisms to be considered when reusing greywater (Rose 1991; Ottosson 2003).Fecal streptococci and fecal coliforms have also been suggested as reliable indicators of the above contaminants (Ottosson 2003).Heavy metal transfer is another underlying problem linked, not only to greywater reuse, but also sludge application in irrigation (Roesner et al. 1994). According to Eriksson et al. (2002) and Rattan et al. (2005), the presence of such toxic metals could be attributed to aging distribution piping and corrosive plumping systems which, if not maintained properly and frequently, could have an adverse effect on the composition of greywater used for irrigation. Rattan et al. (2005) has also found that the plant's vascular system has the ability to accumulate zinc, lead and copper once absorbed from the irrigation water and that these metals have the capacity to tamper with the main functions of vital cellular components. Another alarming issue arises from the possibility of humans consuming contaminated food crops, which are proven to cause numerous abnormal diseases such as lung cancer, anemia and diabetes (Neilen & Marvin, 2008). The aforementioned concerns have propelled the scientists in the field to set certain guidelines when it comes to the use of recycled greywater in order to preserve the health of the farm workers, processors of agricultural products produced using treated greywater, and consumers of such products. For instance, it has been recommended by Lechte, (1992) to store greywater for short periods of time, given its natural ability to breed bacteria and pathogens which might cause bad odors later on. Also, subsurface drip irrigation system has been suggested as an international guideline to avoid direct greywater-crop contact and decrease the potential of microbial transmission to the edible and landscape plant surfaces (NRMMC et al. 2006; WHO 2006). To conclude, further studies and experimental work are still needed to assess the potential risks of using treated greywater, preserve the overall aesthetic appearance, groundwater quality and soil health and encourage public acceptance and practice of such concept (Jefferson et al., 2000).

2.1.6 Standards for Greywater Reuse

At a policy level, Egypt has taken it upon itself to formulate The Egyptian Code for the Use of Treated Wastewater in Agriculture 501/2015 and Law 48/1982 in order to guide the use of treated greywater in agriculture. The Code classifies wastewater into four groups (A, B, C and D), based on the preliminary level of treatment, contaminant concentration limit in effluent water, and most importantly the types of plants that can be used in each grade, as shown in Table 7 and Table 8. Grade A is advanced, or tertiary, treatment that can be attained through upgrading the secondary treatment plants (i.e. Grade B and Grade C plants) to include sand filtration, disinfection and other processes. Grade B and Grade C represent secondary treatment performed at most facilities serving Egyptian cities, townships and villages. They are undertaken by any of the following techniques: activated sludge, oxidation ditches, trickling filters, and stabilization ponds. Grade D is primary treatment that is limited to sand and oil removal basins and use of sedimentation basins.

Table 7: Limit values for Treated Wastewater Reused in Agriculture

Treatment Grade Requirements		**A**	**B**	**C**	**D**
Effluent limit values for physic-chemical parameters (mg/L)	TSS (mg/l)	15	30	50	300
	Turbidity (NTU)	5	Unspecified	Unspecified	Unspecified
	BOD_5 (mg/l)	15	30	80	350
Effluent limit values for biological parameters	E.coli count in 100 ml	20	100	1000	Unspecified
	Nematode cells or Eggs per liter	1	Unspecified	Unspecified	Unspecified

Excerpted from "Egyptian code for the use of treated wastewater in agriculture" 2015

Table 8: Different treatment grades and agricultural groups for Treated Wastewater Reused in Agriculture

Grade	Agricultural Group	Plants\Crops
A	G1-1: Plants and trees grown for greenery at educational facilities, private and public parks	Palm, Saint Augustin grass, cactaceous plants, ornamental palm trees, climbing plants, fencing bushes and trees, wood trees and shade trees.
	G1-2: Fruit crops	Fresh edible crops such as apples, apricots, peaches, grapes, etc
B	G2-1: Dry grain crops	Wheat, corn, barley, rice, beans, lentils, sesame
	G2-2: Trees producing fruits with epicarp.	On condition that they are produced for processing purposes such as lemon, mango, date palm and almonds.
	G2-3: Medical crops	Anise, hibiscus, Cummins, marjoram, mogat, fennel, chamomile, Al-Marmariyah
C	G3-1: Dry grain crops, fruit crops and medical crops mentioned in Group B	Same crops mentioned in Group B, in addition to beet and sunflower plants, on the condition of not using spray irrigation
	G3-2: Non-edible seeds	Wheat, corn and all vegetables seeds, on the condition of planting these seeds in their permanent spots afterwards
	G3-3: All types of seedlings which are later	Athel tamarix (salt tree), pomegranate, bananas, mango, apples, fruit

	transferred to their permanent fields	producing trees, date palm and olive trees
	G3-4: Roses & Cut Flowers	Local rose, eagle rose, onions (e.g. gladiolus).
	G3-5: Trees used for green belts around cities and a forestation of high ways or roads	Casuarina, camphor, athel tamarix (salt tree), oleander, fruit producing trees, date palm and olive trees
	G3-6: Fiber Crops	Flax, jute, hibiscus, sisal
	G3-7: Fodder/ feed crops	Sorghum sp.
	G3-8: Mulberry for the production of silk	Japanese mulberry
	G3-9: Nursery Plants	Nursery plants of wood trees, ornamental plants and fruit trees
D	D4-1: Industrial Solid Crops	All crops that could be turned into coal pills like: willow, poplar and Moringa
	D4-2: Industrial Oil Crops	All organic diesel producing crops like: Jojoba and Jatropha
	D4-3: Cellulose-producing crops	All non-edible crops used for glucose production like: ethanol and acetic acid
	D4-4: Wood Trees	Caya, camphor and other wood trees.

Excerpted from "Egyptian code for the use of treated wastewater in agriculture" 2015

2.2 Greywater Treatment Technologies

Several breakthroughs have been made in the field of greywater treatment, some of which are elementary in principle while others are rather sophisticated. Urban settlements usually rely on centralized wastewater treatment plants to treat residential and industrial waste water. The amount of energy utilized in such systems is usually dependent on the required level of treatment (USEPA, 1998), which involves the operation and maintenance of various advanced physical, chemical and biological units such as membrane bioreactors (Jefferson et al., 2000), coagulation/flocculation units (Pidou et al., 2008), UV/ chlorine disinfection units (Nolde, 2005). Taking into account the principles of sustainability on a household scale, it's always advisable to apply innovative onsite treatment methods such as septic tanks, sand/gravel bed filtration, aquatic filtration, and constructed wetlands (Dallas and Ho, 2004), in order to save on water bills, reduce carbon footprint while maintaining an acceptable water quality, in terms of suspended solids and microorganism removal efficiency. (Jefferson et al., 2004; Ramon et al., 2004).

2.2.1 Physical Treatment Systems

Physical greywater treatment systems comprise filtration and sedimentation. Filtration can be used as a pre-treatment or as a post-treatment method where the filter's porosity and contaminant's particle size directly affect the efficiency of treatment. Filtration as a pre-treatment method includes screen meshes, sand bed filtration, nylon sock type filtration, metal strainers, gravel filtration, and mulch tower system (Boyjoo et al., 2013). Relying on physical greywater treatment processes as the main treatment method is insufficient for greywater treatment, since it does not guarantee adequate reduction of organics, nutrients, and surfactants, except in situations where the organic load strength is extremely low (Li et al., 2009). Hence, the need to use storage and settling tanks as pretreatment methods to mitigate the operational problems that arise such as the clogging of sand filters and membrane fouling.

Chaillou et al. (2011) was able to achieve a mean removal of 30% COD using sand filtration as means of treating greywater sourced from bathrooms. Zuma et al. (2009) was also able to achieve a mean removal of 26% of COD and 52% of TSS using a mulch tower system that consisted of mulch, coarse sand, fine gravel, and coarse gravel. Membrane filtration, microfiltration (MF), ultrafiltration (UF) and nanofiltration (NF) are known to result in a high-quality effluent that is proportional to the molecular mass cut-off (MWCO) of the membrane (Shin et al., 1998; Ramona et al., 2004). For instance, Ramona et al. (2004) was able to achieve a mean removal of 93% COD, 84% TOC and 50% soluble ionic elements using NF as means of treating greywater sourced from showers, which in turn produced high-quality effluent suitable for unrestricted irrigation.

2.2.2 Chemical Treatment Systems

Chemical greywater treatment systems comprise coagulation and flocculation, electrocoagulation, adsorption using granular activated carbon (GAC) and natural zeolites, magnetic ion exchange resin (MIEX), powdered activated carbon (PAC) and advanced oxidation processes (AOPs) such as ozonation, and photocatalysis (Li et al., 2009; Boyjoo et al., 2013). It was proven that coagulation followed by filtration could decrease the suspended solids and organic substances present in light greywater to acceptable standards for non-potable urban reuse (Lin et al., 2005; Pidou et al., 2008). On the other hand, it was found that in order to meet the standards for non-potable urban reuse of heavy greywater, sand/membrane filtration can be used to further treat the effluent from chemical processes (Li et al., 2009; Ghaitidak and Yadav, 2013).

Pidou et al. (2008) was able to achieve a mean removal of 87% BOD_5, 64% COD, 13% Total N and more than 99% of TC and E. coli using coagulation/flocculation as means of treating greywater sourced from showers.

Photocatalysis throughout the use of a catalyst, UV light and an oxidant has also been proven as an efficient chemical technique to reduce organic pollutants and pathogens present in wastewater (Li et al., 2004; Gulyas et al., 2007). For instance, Sanchez et al. (2010) was able to achieve a mean removal of 65% dissolved organic carbon using TiO_2 on light greywater sourced from a hotel, which required further disinfection step to remove the residual TiO_2 from the treated effluent. (Ghunmi et al., 2011).

2.2.3 Biological Treatment Systems

Biological greywater treatment systems comprise Rotating Biological Contactor (RBC), Sequencing Batch Reactor (SBR), Membrane Bioreactors (MBR), Fluidized Bed Reactor (FBR), and Up Flow Anaerobic Sludge Blanket (UASB). Biological systems often come as a medium treatment stage between pre-physical filtration to get rid of accumulated sludge and post-chlorination or use of UV to disinfect microorganisms (Boyjoo *et al.*, 2013). Aerobic biological processes have been proven efficient in reducing organic pollutants and turbidity in heavy greywater in ways that make the treated effluent suitable for long storage periods before reuse (Li *et al.*, 2009).

The MBR technology in which a combination of biodegradation and membrane filtration is adopted, has been found to be a viable mechanism to reduce organic pollutants and microbial contaminants present in greywater, where it eliminates the additional cost associated with post filtration/disinfection. It was observed from literature that various MBR systems achieved the following removal rates: turbidity (98-99.9%), TSS (around 100%), BOD_5 (93-97%), COD (86-99%), total N (52-63%), PO_4–P (10-40%), total P (19%), and FC (99.9%); (Ghaitidak and Yadav, 2013). It was also proved that the high-grade effluent quality which contains high organic loading rate can be economically recycled in collective urban residential complexes (Lazarova et al., 2003)

The RBC and FBR were also proven efficient in reducing biological contaminants present in light greywater with initial BOD_5 concentration of 50-300 mg/l up to 5 mg/l (Nolde, 2000). Friedler *et al.* (2006) was able to achieve a high-grade quality effluent when treating light greywater with initial BOD_5 and COD concentrations of 59 and 158 mg/l, respectively using RBC. SBR in which sequenced equalization, biological treatment, and secondary clarification takes place in the same Reactor tank has been proven to be an efficient light greywater treatment technology in small communities where the effluent meets the NH_4–N, BOD_5, and COD standards for wastewater reuse (Lamine *et al.*, 2007).

Despite the low cost associated with USAB system installation, the anaerobic treatment system was proven to be a poor option for greywater recycling with average removal rates of 40% COD, 25.75% TN and 17.9% TP (Leal *et al.*, 2011). However, it was recommended to use USAB prior to aerobic treatment, along with a final disinfection step to achieve acceptable effluent quality (Ghunmi *et al.*, 2011).

2.2.4 Natural Treatment Systems

Natural greywater treatment systems combine physical filtration throughout the use of natural media like sand, gravel, rocks and biological degradation throughout the use of biofilm, plant roots, slugs and earth-worms. The advanced treatment technology which is mainly used to treat heavy greywater (Boyjoo et al., 2013) includes aquatic filtration, horizontal-flow constructed wetland (HFCW), vertical-flow constructed wetland (VFCW), anaerobic filters, and vertical-flow filter (VFF). The aforementioned technologies rely mostly on chemical precipitation and adsorption along with plant uptake processes in the removal of nutrients such as phosphorus and nitrogen (Kivaisi, 2001).

A. Wetlands

Engineered wetlands utilize solar energy, plants and natural occurring aerobic and anaerobic microorganisms in the soil to degrade the organic and toxic contaminants and absorb nutrients present in wastewater. Constructed wetlands simulate the biological, physical and chemical processes that occur naturally in the soil to purify water (DeBusk 1999). The recently discovered technology has spread widely throughout Africa, Asia, Europe, Australia and the United states as a cost-effective treatment mechanism in aquatic systems, especially in countries with low income and limited resources (Boyjoo et al., 2013). Despite the far-reaching effect these wetlands have in enriching soil and recharging groundwater, their large footprint could deem them impractical for many residential applications.

Constructed wetlands are classified into free water surface (FWS) where water flows above ground and soil is planted with either floating or emergent aquatic plant species, subsurface flow (SF) where water is submerged below a natural media surface and soil is planted with emergent plant species. Finally, there are hybrids where both arrangements take place. Subsurface flow wetlands are generally considered the more viable option due to their limited surface area requirements (Kuchta, and Sarana, 2008) and their ability to reduce bad odors and undesirable insect exposure (EPA 2002). Subsurface flow wetlands are further classified into horizontal where water flows parallel to surface level and vertical where water flows evenly across the surface and percolates through the root zone of the plant. Constructed wetlands systems have been proven to achieve average removal rates of 94% TSS, 99% BOD_5, 82% COD and 54% total N (Ghaitidak and Yadav, 2013).

B. Aquatic Filtration

Aquatic plant systems utilize floating and submerged aquatic macrophytes to treat wastewater. The macrophytes provide a suitable medium for oxygen transfer to the microorganisms responsible for degrading organic matter in wastewater. They also absorb some of the nutrients and heavy metals which would later be stored or metabolically consumed by the plant (Lakshman, 1987; Abbasi, 1987; Heaton et al., 1987; O'Keeffe et al., 1987; WPCF, 1990; and others).

- Floating Plants

  Free floating aquatic plants such as water lily, water hyacinth, Pennywort and alligator weed grow above water surface where they utilize solar energy, carbon dioxide, oxygen present in air along with dissolved nutrients present in water to establish various photosynthetic and metabolic activities. The roots of the plants provide a rich medium for microorganisms to thrive and biodegrade organic constituents in their water medium (Reddy et al., 1989). Floating macrophytes could provide a viable option for anaerobic bacterial degradation to take place due to their far-growing mats which hinder the passage of light and wind and in turn proper gas transfer to the surrounding water. The extensive root system of some of the floating aquatic plants could also enhance the sedimentation and removal of suspended solids present in waste water (Dinges. 1982: EPA. 1988: Metcalf& Eddy. 1991). Some of the operating parameters that could be tackled to further enhance the performance of treatment using floating aquatic plants are temperature, nutrient content of wastewater, the recycle ratio and the harvest rate and frequency.

- Submerged Plants

Submerged aquatic plants such as Elodea canadensis, E. nutallii, Egeria densa, Ceratopliyllum demersum, Potamogetonfoliosus. And Hydrilla verticillate draw oxygen, carbon dioxide and nutrients needed to establish their metabolic activities from their water medium (Dinges, 1982). The roots of the plants provide a rich medium for microorganisms to thrive and biodegrade organic constituents in their water medium. For efficient wastewater treatment the aforementioned plants, anaerobic as well as highly turbid waters must be avoided. Hence, submerged aquatic plants are best used during the final polishing stage of wastewater treatment. (Eighmy et al. 1987: Reed et aL. 1988).

2.3 Incorporation of Sustainable Development and Biophilic Design in Landscape Irrigation

Sustainability is defined as "the principle of meeting today's needs without sacrificing the right and the ability of future generations to meet their own needs"(WCED, 1987). Ensuring the sustainability of cities is ensuring the livability and continuity of the living standards of those living in cities and those living in the future. With an ecological approach, cities are living creatures living in a certain area and interacting with each other, and cultural ecosystems formed by their inanimate environment. For this reason, cities should be in harmony with other ecosystems such as lakes, coastal and forest ecosystems in their environment and should not harm them at least. Biophilic Architecture is a systematic study of the concepts of nature, planning and design; an occupational discipline dealing with planning, management and space design of ecological-economic-functional, and therefore sustainable, by evaluating natural and cultural resources in the correct way, by bringing together art, science, engineering and technology (Fromm, 1973).

The Biophilia Hypothesis, which claims that humans possess a biologically based attraction to certain aspects of the natural environment and that their well-being depends, to a great extent, on the relationships with the surrounding natural world (Wilson, 1978; Wilson, 1984; Kellert, 1997; Kellert, 2002; Kellert, 2008; Ulrich, 1993). Biophilia settlements, centering on the conservation of all-natural life forms in relation to nature and living areas and enabling them to experience the indispensability of balancing with the cooperative learning process, can be used as a tool for sustainable urban development (Olgun and Demet Yücel, 2012).

The following case studies incorporate the concept of sustainability and biophilic design into landscape irrigation using treated wastewater:

2.3.1 The Sidwell Friends School

Founded in 1883, the Sidwell Friends School is for student's pre-K through 12th grade. In 2006, a 39,000 square-foot, LEED platinum expansion to the existing 55-year-old middle school was completed (Figure 2). The school promotes Quaker values including caring for the environment, which guided the design process to focus on environmentally sensitive design solutions (Malin, 2007).

The preliminary design phase included plans for onsite wastewater treatment using an indoor Living Machine. Bill Reed, American Institute of Architects, proposed an outdoor option, using constructed wetlands as part of the landscape. The school received approval for the system as a pilot study, from the Washington D.C. Health department. Part of the approval included a quality monitoring protocol (Malin, 2007). The new landscape includes a 3,000-gallon-per-day SSF as part of the wastewater treatment (Figure 3). Prior to entering the SSF, the wastewater is pre-treated in an anaerobic septic tank located in the school's basement which settles suspended solids out of the wastewater. The treated wastewater then exits the building as effluent and is pumped to a three-terrace SSF where it resides for three to five days before exiting the system (CGBC, 2011a). Finally, the effluent runs through a trickling filter and UV light. The treated water is stored in greywater tanks prior to reuse for flushing, irrigation, and cooling towers (ASLA, 2013).

With the assistance of wastewater engineer consultants, over 80 plant species were chosen based on their performance for waste removal and adaptability to the soils. In addition to treating wastewater, the plants are an example of using native species in the landscape. The treatment system is integrated into the school curriculum in several ways, including water testing by students (ASLA, 2013).

Figure 2: Sidwell Friends School Courtyard

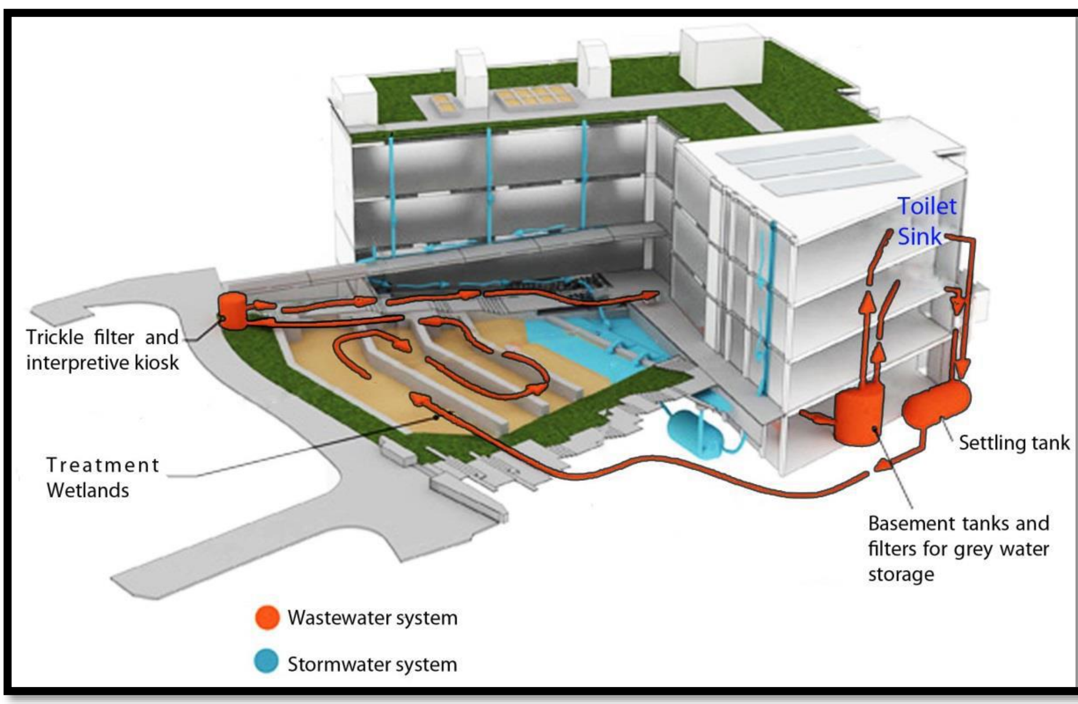

Figure 3: Wastewater Flow in the Landscape (Andropogon Associates)

2.3.2 Saginaw Metal Castings Operations

Owned by General Motors, Saginaw Metal Castings Operation (SMCO) is a 400-acre property located along the Saginaw River in Saginaw, Michigan. Thirty-five acres of the property are set aside for wildlife habitat projects (WHC, 2013).

In 2002, SMCO proposed a wetlands demonstration area in the lobby of their office building (Figure 4). The scope of the project included a diorama, an aquarium, signs, and diagrams explaining the importance of wetlands. The landscape architect proposed the use of a working SSF as an alternative to the original concept of an indoor demonstration area (Designscapes, 2013).

Figure 4: Subsurface Flow Wastewater Treatment Wetland at Saginaw Metal Castings

The SSF is designed to treat 1,200 gallons-per-day from the office building. As seen in in the landscape plan (Figure 5) the process begins as wastewater is pumped from the sanitary sewer into a septic tank for anaerobic treatment. Effluent from the tank is gravity fed through the SSF and into the water feature pond. The effluent is also used for irrigating plants around the office complex. Water exiting the SSF has levels of nitrogen, phosphorus, and TSS 90 percent lower than when it exits the septic tank (WHC, 2013).

Prior to planting, EPDM liner for the SSF was extended across the entire landscape. As water flows horizontally through the system; the whole landscape is irrigated. Through the use of angled grading, different water zones were created allowing for the use of marginal plants and plants accustomed to lower water use (Designscapes, 2013).

Figure 5: Saginaw Metal Castings plan (Designscapes, 2013)

2.3.3 Advanced Green Builder Demonstration Building

Located in Austin, Texas and built in 1998, the Advanced Green Builder Demonstration (AGDB) is a structure designed to demonstrate sustainable building techniques. The building is part of the Center for Maximum Potential Building Systems (CMPBS); a nonprofit designed to demonstrate sustainable building techniques. Funding for the AGBD came from a $100,000-grant provided by the State of Texas in partnership with the U.S. Department of Energy. Outside of the building is a 13,200-gallon rainwater harvesting system (CMPBS, 2013). Surrounding the two rainwater tanks is an SSF used to treat wastewater from the AGBD (Figure 6). The cisterns and SSF are incorporated into the main entryway of the AGDB.

The system starts with low-flow toilets connected to a septic tank for primary treatment. Water from the tank travels through an SSF originally planted with carizzo (Arundo donax) and common reed (Phragmite australis). The plants were replaced with cana lilies (Cana x generalis), calla lilies (Zantedeschia aethiopica), irises (iris sp.), and other less invasive species. After passing through the SSF, wastewater is held in preparation for use in subsurface irrigation.

The wastewater treatment design standard for water use in Austin and Travis County is 160 gallons per capita per day (City of Austin, 2010). Through the use of low-flow fixtures in the AGDB, water use was decreased to 25 gallons of water per person per day allowing for an SSF 83 percent smaller than required by city standards (CMPBS, 2013). Although the AGDB was designed to be an example for residential use, it currently houses the main offices for the CMPBS.

Figure 6: Entry to the Advanced Green Demonstration Building, Subsurface Flow Wetland Highlighted on Right Side of Walk (Courtesy Jesse Wilson)

2.4 Mechanism of Removal

Borin & Solvato (2011) state that there are uncertainties regarding the prevailing removal mechanisms of pollution parameters existing in greywater because they also depend on a series of factors such as plant species, system configuration and climatic conditions.

Root structures in different aquatic plants can affect nutrient removal because there are different oxidic environment provided in the rhizosphere (Brix, 1997). For instance, water hyacinth roots are resembling of branching clusters, thus the number of bacterial adhesion per unit mass (g) is high. In other words, the extensive root zone of water hyacinth which is famous for its rapid growth (biomass can be doubled in 6 days) provides large area for microorganisms attached and therefore stimulate better biodegradation of organic matters and other nutrients such as nitrogen and phosphorus in greywater (Reddy and Sutton, 1983; Kivaisi, 2001). On the other hand, Brix, [1997] reported that roots and rhizomes of reeds are hollow and contain air-filled channels that are connected to the atmosphere for the purpose of transporting oxygen to the root system. The majority of this oxygen is used by the roots and rhizomes themselves for respiration, but as the roots are not completely gastight, some oxygen is lost to the rhizosphere.

The use of water hyacinth as the functional unit in wastewater treatment systems has been increasingly demonstrated and treatment regimens developed as a result of successful pilot projects (Brix, 1989). According to (Reddy et al., 1983), the presence of plants in wastewater depletes dissolved CO_2 during the period of photosynthetic activity and an increase in DO of water, thus creates aerobic conditions in wastewater, which favors the aerobic bacterial activity to reduce the BOD_5 and COD (Mahmood et al., 2005).

It is also reported that suspended particles can be removed in the water hyacinths treatment systems through filtration and sedimentation (Brix, 1998). However, according to Kim et al. (2008) the removal efficiency mostly depends on the retention time in wetland systems. As suspended solids pass through the plant roots (similarly, to filtration process), they can be trapped, accumulate, and eventually settle under the force of gravity or become metabolized by microorganisms, while particulate matter sinks to the bottom.

The evapotranspiration plays an additional important role by increasing the hydraulic retention time in wetland treatment systems. It is positively related to the impurity absorption, volatile compound emission into the atmosphere, and water purification capability index of plants.

Moreover, nitrates are commonly present in various forms in greywater and are important for plant growth. Removal of nitrogen conventionally takes place through several processes like plant uptake, ion exchange, ammonia (NH3) volatilization, nitrification and denitrification (Gersberg et al, 1983; Chang-gyun et al, 2009; Vipat et al, 2008). Habrel and Perfler (1991) indicated the pathway of N-removal through the plant uptake as insignificant while Breen (1990) considered such plant uptake as a dominant mechanism for nitrogen removal.

Phosphate is also considered a main nutrient, significantly needed for the functioning of terrestrial as well as aquatic ecosystems. It is required for better plant growth and is a limiting key factor for vegetative productivity. Carr et al. (2011) state that the substantial amount of nutrients is acceptable in the treated effluent once they reduce the need for chemical fertilizers used to increase crop productivity.

2.5 Objectives

The overarching aim of this thesis is to provide detailed information on the performance of simple, robust and low-cost alternatives for on-site treatment of greywater. It is achieved specifically in the following objectives:

- Synthesize laboratory grade greywater that simulate contaminants present in real greywater
- Investigate the effect of three local aquatic plants on the treatment performance of synthetic greywater
- Investigate the effect of different hydraulic loading rates on the treatment performance of synthetic greywater
- Investigate the effect of different plant densities on the treatment performance of synthetic greywater
- Study the performance of a pilot scale aquatic filtration system in treatment of real greywater

CHAPTER 3: Materials and Methods

3.1 Introduction

This study was performed in five phases. Since real greywater is highly variable in quality and hard to obtain in a significant reliable quantity, synthetic greywater was formulated in the lab to run the different experiments of the study. Synthetic greywater was used to optimize the design/operating conditions of the proposed treatment system. Real greywater was also used to test the proposed treatment system at the optimum design/operating conditions obtained from the use of synthetic greywater. The next sections will discuss the laboratory and pilot-scale set-ups of the different experiments in the current work. All experiments were conducted in the facilities of the American University in Cairo (AUC).

3.2 Experimental Set-up

The current study was performed in five different phases, as follows:

- Phase I: Synthetic Greywater Preparation
- Phase II: Lab Scale Greywater Treatment System
- Phase III: Pilot Scale Greywater Treatment System – Effect of Hydraulic Loading Rate
- Phase IV: Pilot Scale Greywater Treatment System – Effect of Plant Density
- Phase V: Pilot Scale Greywater Treatment System – Real Greywater

Phase I was conducted to synthesize greywater at the environmental lab that stimulates the organic and inorganic constituents of light greywater as reported in literature. The predetermined composition of synthetic greywater served as a way to ensure consistency and repeatability of the end results throughout Phase II, III and IV.

Phase II was designed to select the plant species, among three aquatic plants, that will be utilized in greywater treatment and will be used in Phases III, IV and V.

Phase III was conducted to investigate the effect of hydraulic loading rate on the performance of aquatic filtration system on the treatment of synthetic greywater. The plant used in this phase was selected based on the results obtained from Phase II.

Phase IV was designed to investigate the effect of different densities of the plant selected from Phase II on the treatment of synthetic greywater using the optimum hydraulic loading rate obtained from Phase III.

Phase V was conducted to study the performance of the aquatic filtration system in treating real greywater when using the optimum operating conditions obtained from Phase III and Phase IV.

3.3 Phase I: Synthetic Greywater Preparation

3.3.1 Greywater Composition

Different mixtures of different chemicals/materials were tested to obtain the desired greywater composition that represents the average greywater quality reported in literature. The mixtures were prepared by mixing different concentrations of the chemicals listed in Table 9. with tab water. The mixtures were then sampled for the analysis of different water quality parameters.

The recipe of synthetic greywater that will be used to conduct the experiments of Phase II, III and IV is shown in Table 10.

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Table 9: Synthetic greywater formulation from literature (Hourlier et al., 2010)

Product	Purity	Function	PSD*							Conc. (mg/l)
Lactic acid	> 85 %	acid produced by skin		2	3	4			7	100
Bentonite or Cellulose	NA > 90 %	suspended solids				4				100
Sodium dodecyl sulfate	> 85 %	anionic surfactant			3			6	7	50
Glycerol	99 %	denaturant, solvent, moisturizing agent	1	2	3	4	5	6	7	200
$NaHCO_3$	> 99 %	pH buffer				4				70
Na_2SO_4	99 %	viscosity control agent				4	5			50
Septic effluent**		microbiological load					5			10

NA: not available. *PSD: pollution stimulated is due to: (1) human body (2) shampoo and shower gel (3) soap (4) deodorant (5) tooth paste (6) shaving and moisturizing cream (7) make-up and make-up remover

** Septic effluent: wastewater effluent which is collected in an underground septic tank. It constitutes from feces, urine and other waste matter that is made of harmless using bacteria

Table 10: Synthetic greywater formulation (current study)

Product	Function	PSD*							Contribution of material to pollution parameter	Range of Tested Conc. (g/l)
Sodium dodecyl sulfate	anionic surfactant			3			6	7	pH, COD, BOD_5, TDS, turbidity, NH_3-N, PO_4-	0.01-0.15
Sodium hydrogen carbonate	pH buffer				4				TDS, color, COD, BOD_5	0.035-0.125
Sodium Sulphate	viscosity control agent				4	5			TDS, color	0.025-0.1
Cellulose	suspended solids				4				COD, BOD_5, TSS	0.01-0.05
Lactic acid	acid produced by skin		2	3	4			7	pH, NH_3-N, PO_4-, COD, BOD_5	0.016-0.08 ml/l
Clay soil	suspended solids					5			TSS, color, turbidity	0.1-0.15
Septic effluent**	microbiological load					5			TSS, COD, BOD_5, FC	1-25 ml/l

*PSD: pollution stimulated is due to: (1) human body (2) shampoo and shower gel (3) soap (4) deodorant (5) tooth paste (6) shaving and moisturizing cream (7) make-up and make-up remover
**Septic effluent: wastewater effluent which is collected in an underground septic tank. It constitutes from feces, urine and other waste matter that is made of harmless using bacteria

3.3.2 Analysis of Synthetic Greywater Samples

All chemicals and reagents used in the laboratory test procedures were of analytical grade and standard approved make. The glassware, containers and bottles used for the sampling and analysis were initially cleaned with tap water followed by nitric acid before rinsing with distilled water. Standard solutions and necessary reagents were prepared on a regular basis to achieve the best possible results. "Blank control" tests were conducted whenever necessary in order to determine the background concentrations during the sample analysis. Samples were vigorously shaken to obtain homogeneous quality before they were pipetted out for any test analysis. Instrumental calibrations were performed on a regular basis. All experimental development, calibrations, standard preparations, experimental methods, data generation, and documentation of activities were conducted following documented literature guidelines, as shown in Table 11.

Table 11: Standard methods used for tested water quality parameters

Parameter	Method	Instrument/ Model	Country of Manufacturing
DO	Standard Method for the Examination of Water and Wastewater – Method #4500-O G	HQ Model 30 D	USA
BOD_5	Standard Method for the Examination of Water and Wastewater – Method #5210 B	-	-
COD	Standard Method for USEPA approved HACH – Method# 8000	HACH Spectrophotometer DR/2000	USA
Phosphates	Standard Method for USEPA approved HACH – Method# 8190 for preparation and Method# 8114 for analysis	HACH Spectrophotometer DR/2000	USA
Nitrates	Standard Method for USEPA approved HACH – Method# 8038	HACH Spectrophotometer DR/2000	USA
Ammonia	Standard Method for USEPA approved HACH – Method# 8038	HACH Spectrophotometer DR/2000	USA
Total Suspended Solids	Standard Method for the Examination of Water and Wastewater – Method #2540 D	-	-
Turbidity	Standard Method for USEPA approved HACH – Method# 8237	HACH Spectrophotometer DR/2000	USA
Color	Standard Method for USEPA approved HACH – Method# 8025	HACH Spectrophotometer DR/2000	USA
pH	Standard Method for USEPA approved HACH – Method# 4500-H^+ B	HACH Spectrophotometer DR/2000	USA
TDS	Standard Method for USEPA approved HACH – Method# 8160	HACH Conditioning TDS Meter	USA
FC	Standard Method for the Examination of Water and Wastewater – Method #9222-D	-	-

3.4 Phase II: Lab scale greywater treatment system

3.4.1 Plants selection and acclimatization

Water hyacinth (*Eichhornia crassipes*), papyrus reed (*Cyperus papyrus*) and common reed (*Phragmites australis*) are common aquatic plants that grow near to river banks and drains in Egypt These plants are known for their ability to treat wastewater and are commonly used in constructed wetlands and aquatic filtration systems (Wolverton and McDonald, 1979). Therefore, they were selected to be used in the experiment of Phase II. The plants were collected from El-Mansouriya Drain in the Giza Governorate and transported to the greenhouse on the roof level of the Science and Engineering building at AUC. The plants were thoroughly washed after collection and were allowed to grow in a nutrient rich solution for two consequent weeks prior to acclimatization.

The acclimatization was performed to avoid the shock effect of the new conditions on the plant performance. The acclimatization process included the following steps: 1) the plants were first fed regular tab water. 2) After four days, makeup water (25% synthetic greywater and 75%-tab water) was added to compensate for the amount evaporated. 3) After 8 days, makeup water (50% synthetic greywater and 50%-tab water) was added to compensate for the amount evaporated. 4) By the end of 12 days, the makeup water added to compensate for the amount evaporated consisted of 100% synthetic greywater. After twelve days of gradual acclimatization, the plants were transported to their designated containers to start the actual experiment. The synthetic greywater used in this phase was prepared according to the recipe obtained in Phase I.

3.4.2 Description of setup and design considerations – Phase II

The experimental setup in Phase II (Figure 7) consisted of the following units:

1) Storage tank (capacity of 45 L) which acted as a reservoir for prepared synthetic greywater (Figure 7- 3)

2) Flow control valves to adjust and control the flow entering the sponge filter and planter bed Reactors (Fig 4)

3) Sponge tank (capacity of 125 L) (Figure 7- 2)

4) Submersible pump which will carry the prepared synthetic greywater from the storage tank to the bed Reactors (Fig 6)

5) Three planter bed Reactors, each planted with a different aquatic plant (capacity 14 L) (Figure 7- 1)

6) Control bed Reactor (capacity 14 L) (Figure 7- 4)

7) Sampling valves located at the bottom of the planter bed and control bed Reactors (Figure 7- 5)

The three planter bed Reactors were used to investigate the performance of water hyacinth, common reed and papyrus reed in treating synthetic greywater when operating in a batch mode. The sponge filter was installed as a pretreatment unit to remove soap suds from greywater. Synthetic greywater was first introduced from the storage tank to the sponge filter by opening the flow control valve installed on a pipe connecting the two tanks. After filling the sponge filter with greywater, the valve is closed and water is pumped from the storage tank to fill three planter bed Reactors and a control bed Reactor. Afterwards, the control flow valve is closed and the experiment starts. The planter bed and control bed Reactors took approximately one hour to be filled with pre-treated greywater from the sponge filter. The control bed Reactor was partially covered with a cardboard (covering 75% of its surface area) to simulate the plant coverage in the planter bed Reactors.

Figure 7- 3: Storage tank

Figure 7- 2: Sponge tank

Figure 7- 1: Planter bed Reactors

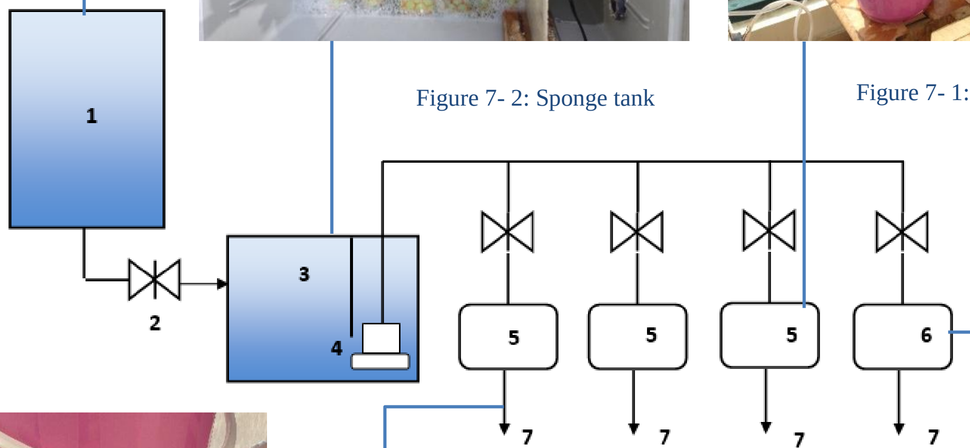


Figure 7- 4: Control bed Reactor

Figure 7:Schematic diagram of the experimental set-up in Phase II: 1) storage tank; 2) flow control valves; 3) sponge filter; 4) submersible pump; 5) planter bed Reactors; 6) control bed Reactor 7) treated greywater effluents and sampling points

Figure 7- 5: Sampling point

3.4.3 Sampling and sample analysis – Phase II

Samples of 1 L volume were collected from the bottom of each planter bed as well as the control bed Reactor by opening the sampling valves. Samples were collected after the addition of makeup water which was added to compensate for the water lost by evaporation/evapotranspiration. The makeup water used was deionized water (DI) and it was added to the water inside the Reactor to raise its level to the initial/previous water level after the previous sampling event. The contents of each Reactor were then well mixed prior to sampling. After sampling, the new level of water in the Reactor is marked. The samples were collected at a fixed time of the day (10:30 AM) after 2, 5, 8, 13, 17 and 20 days from the start of the experiments. The collected samples were tested for pH, turbidity, color, TSS, TDS, NH_3-N, PO_4-, COD, BOD_5 and fecal coliform. The analytical procedures for all parameters are similar to that previously discussed in section (3.3.2) of Phase I.

3.4.4 Determination of evaporation/evapotranspiration – Phase II

The initial plant wet mass in all planter bed Reactors for all plant types was 2.36 kg (4.2 g wet mass/cm^2 of water surface area). Rate of evaporation/evapotranspiration ($Q_{evp.}$) was calculated for all Reactors using the following equation:

$$Q_{evp.} = (V_{initial} - V_t)/t$$

Where:

$V_{initial}$: Initial water volume in the Reactor before evaporation/evapotranspiration took place

V_t: Water volume at time (t) before the addition of the makeup water

t: The time duration for the evaporation/evapotranspiration of that amount of water

Evaporation/evapotranspiration rate was calculated in each Reactor after 2, 5, 8, 13, 16 and 19 days from the start of the experiment. The amount of water lost in each Reactor was compensated by adding DI water. Ambient temperature at the greenhouse was monitored and water temperature in each bucket was recorded on each sampling event using a handheld thermometer.

3.5 Pilot scale system

In phases III, IV and V, a pilot scale system was designed and fabricated for the treatment of greywater. The pilot scale system is basically a continuous flow aquatic filtration system that utilizes water hyacinth for the treatment of greywater. A detailed description on the pilot scale system will be explained in the following section.

Different operating/design parameters of the pilot scale system were investigated for the treatment of greywater in the next three phases. These parameters include the hydraulic loading rate, the plant density, and the ability of the system to withstand shock loading (both hydraulic and organic). Synthetic greywater was used to obtain the recommended operating/design parameters (Phase III and IV. Then, the system was tested to treat real greywater using the recommended operating/design parameters obtained from Phases III and IV (Phase V).

3.6 Phase III: Pilot scale system - Effect of hydraulic loading rate

3.6.1 Description of setup and design considerations – Phase III

The experimental setup (Figure 8) comprises the following layout:

1) Storage tank (capacity of 2000 L) which acts as a reservoir for prepared synthetic grey water. Synthetic greywater was prepared daily and was added to this tank (Figure 8- 2)

2) Close-coupled centrifugal pump with peripheral impeller and maximum capacity of 100 l/min was operated 24 h to keep the constituents of greywater in the storage tank in suspension so that it would enter the aquatic filtration system homogeneously throughout the time of the day during the experiments

3) Submersible pump for pumping the synthetic greywater from the storage tank to the five Reactors

4) Diaphragm pump which was connected to a voltage source to adjust its flow rate to the total desired one. It was used to aid the submersible pump in pumping synthetic greywater (Figure 8- 4)

5) Flow control valves to adjust inflow and outflow in and from different Reactors (Figure 8- 1)

6) Five Reactors designed as plug flow systems. The Reactors were made of PVC and assembled at a plastic workshop in Cairo. All tubing connected to the planter bed Reactors was made of plastic. Each Reactor contains two PVC sheets; one at the inlet and one at the outlet as baffles to direct the motion of the flow and prevent short circuiting. Greywater flow in these Reactors. The Reactors also contain water hyacinth plants floating on the surface of greywater inside these Reactors. (Figure 8- 3)

Each Reactor is 100 cm in length, 30 cm in width and 60 cm in depth. The first baffle sheet is installed at a distance of 5 cm from the inlet of the Reactor and depth of 35 cm from the top of the Reactor and the second baffle sheet is installed at a distance of 5 cm before the exit of the Reactor and a height of 45 cm from the bottom of the Reactor. The water depth in each Reactor was maintained at 50 cm during all experiments. Figure 9 shows a section elevation in a Reactor used in the pilot scale system.

Figure 8- 2: Storage tank

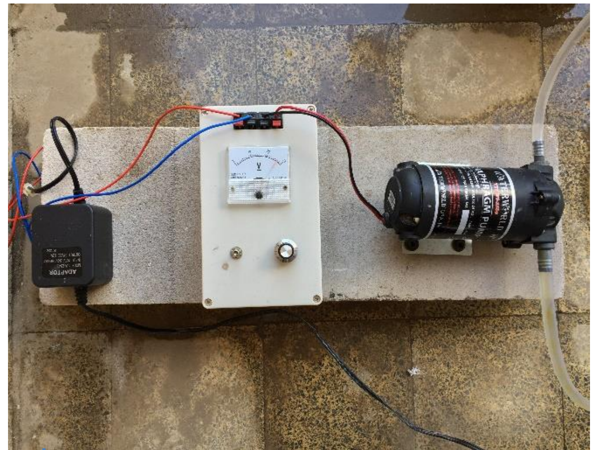


Figure 8- 4: Diaphragm pump

Figure 8- 3: Five Reactors

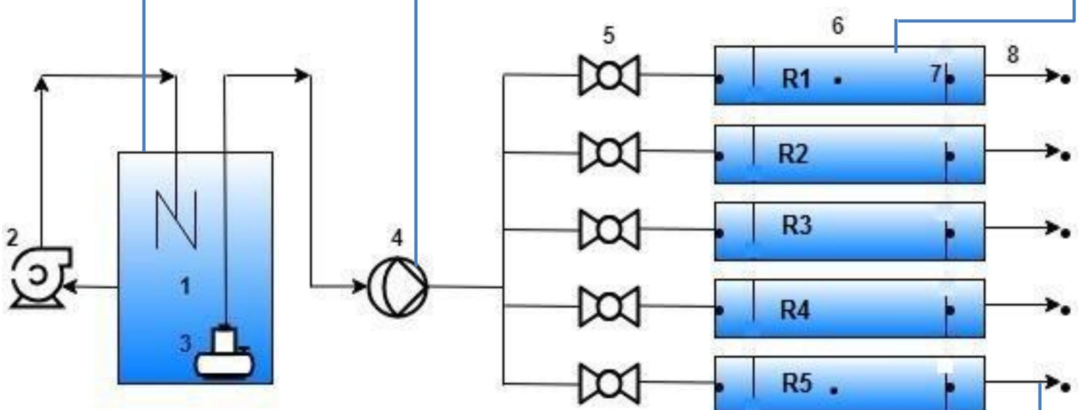


Figure 8: Schematic diagram of the experimental set-up in Phase III: 1) storage tank; 2) centrifugal pump; 3) submersible pump 4) Diaphragm pump 5) Flow control valves; 6) planter bed Reactors; 7) sampling points; 8) treated greywater effluents

Figure 8- 1: Flow control valves and sampling points

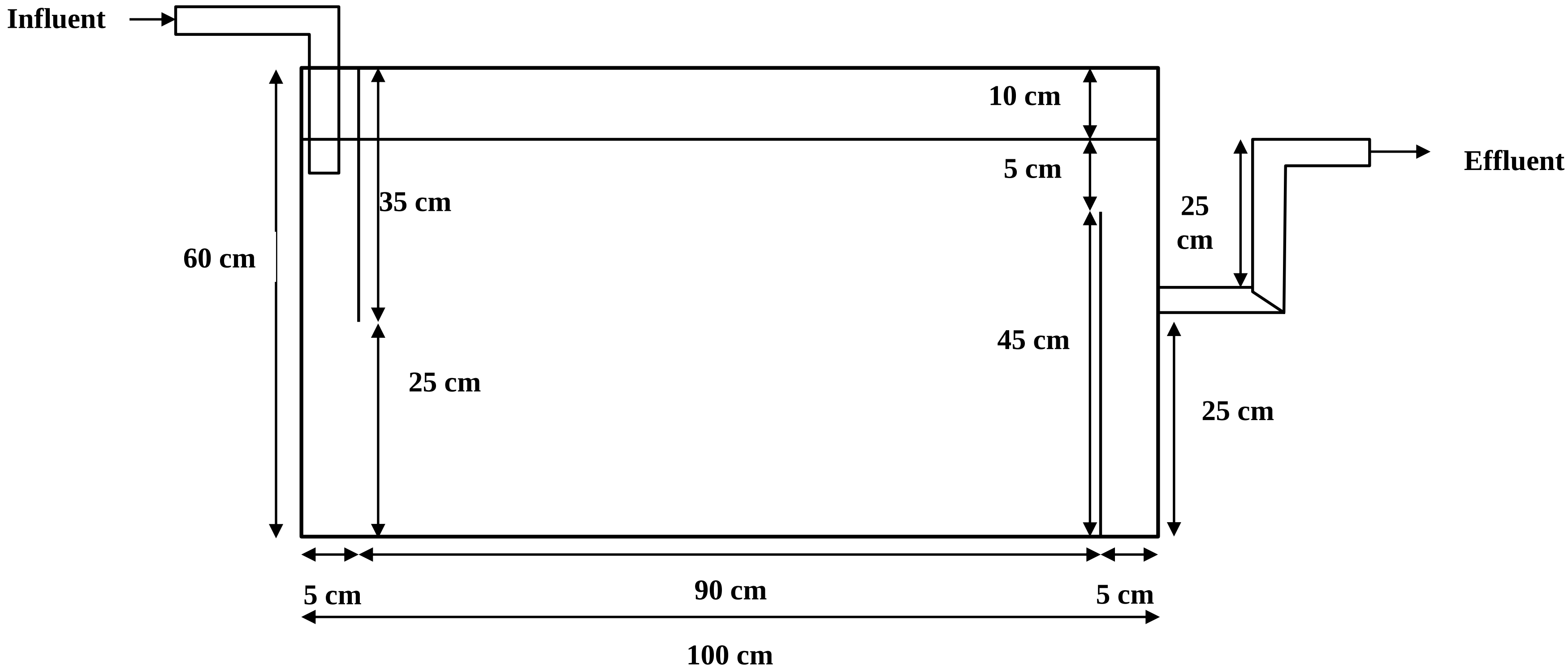


Figure 9: Section elevation in a Reactor of the pilot scale system in Phase III

3.6.2 Operating conditions – Phase III

The pilot scale system in Phase III was run using synthetic greywater to investigate the effect of different hydraulic loading rates on the treatment performance of synthetic greywater. Each Reactor contains the same wet mass of water hyacinth. A total amount of 1900 L of synthetic greywater was prepared daily based on the desired organic loading rate in each Reactor. Previous studies have shown that the maximum BOD5 removal rates in a pilot scale water hyacinth based secondary treatment system occur at organic loading rates greater than 170 kg BOD_5/ha/d (DeBusk et al., 1989). Hence, Table 12 shows the different hydraulic/organic loading rates that were used to operate the Reactors in the current experiment.

The flow rate required to enter each planter bed Reactor was calculated using the following equation:

OLR = (Q*C)/As

Where:

OLR: Organic loading rate (g BOD5/ m2 of water surface area.d)

Q: Discharge from Reactor (m3/d)

C: Desired concentration of BOD = 69 g/m3

As: Surface area of water in the Reactor = 0.3 m2

Table 12: Operation conditions in Phase III

Reactor	Desired[1] OLR (g BOD_5/m^2. d)	Actual[2] OLR (g BOD5/m^2. d)	Desired HLR (m^3/m^2. d)	Actual HLR (m^3/m^2. d)	Desired Q (m^3/d)	Actual Q (m^3/d)
R1	120	111.8±4.8	1.74	1.62±0.07	0.52	0.485±0.02
R2	98	96.6±3.5	1.42	1.4±0.05	0.43	0.42±0.016
R3	68	62.1±4.8	0.99	0.9±0.07	0.3	0.27±0.02
R4	44	43.5±2.1	0.64	0.63±0.03	0.2	0.19±0.01
R5	20	18.6±2.1	0.29	0.27±0.03	0.086	0.081±0.008

1: Desired parameters that result from values in literature and calculated values. 2: Actual parameters that result from experimentations

3.6.3 Sampling and sample analysis – Phase III

A 1 L sample was collected from the storage tank (as representative of raw synthetic greywater), the influent, the effluent of each Reactor and intermediate points in between along the Reactor length. The influent sample is a composite of the greywater entering each of the five Reactors. Samples from the influent and the effluent of the Reactors were collected at a fixed hour of the day after 8, 12, 15, 19 and 20 days from the start of the experiment. While, samples from intermediate points in between along the Reactor length were only collected after 15, 19 and 20 days from the start of the experiment. The collected samples were tested for pH, turbidity, color, TSS, COD and BOD_5. The analytical procedures of testing were similar to that previously discussed in section (3.3.2) of Phase I.

3.6.4 Determination of evaporation/ evapotranspiration and plant growth rates – Phase III

Rate of evaporation/ evapotranspiration ($Q_{evp.}$) was calculated for all Reactors using the following equation:

$$Q_{evp.} = Q_{influent} - Q_{effluent}$$

Where:

$Q_{influent}$: The flow rate entering the Reactor

$Q_{effluent}$: The flow rate exiting the Reactor

The initial average plant density (Plant wet mass basis) were 1.758±0.32, 1.757±0.269, 1.737±0.333, 1.668±0.361 and 1.77±0.371 kg/m^2 for Reactor 1, Reactor 2, Reactor 3, Reactor 4 and Reactor 5, respectively. Plant growth rate was measured every 3 days and maintained at the original density (±10%) over the period of 18 days. Excess plants were removed and additional plants were added (If needed) to reach the original set plant density in each Reactor. Air temperature was monitored using online weather forecasts and water temperature in each Reactor was recorded during each sampling event using a handheld thermometer. Influent and effluent flow rates were measured using a beaker and a timer.

3.6.5 Effect of hydraulic shock/organic loading – Phase III

An experimental run was carried out to investigate the resilience of the pilot scale system when subjected to shock loading during a regular day. The pilot system was tested in this experimental run at two HLR values that provided the best performance of the system in phase III experiments. Shock loading occurs when high loads of contaminants are present in greywater due to higher use of bathroom facilities or kitchen. The duration of the shock loads may last from few minutes to 1-3 hours depending on the size of the facility. To run the experiment, the flow rate was increased three times its original value for four hours in each Reactor to simulate the peak condition. Then, during the following twenty hours, the two Reactors were operated at the original flow rate. A 1 L sample was collected from the effluent of each Reactor after contact time of 1 h, 2 h, 3 h, 4 h, 8 h, 12 h and 24 h from the start of the shock loading. The collected samples were tested for turbidity, TSS and COD. The analytical procedures of TSS, turbidity and COD were similar to that previously discussed in section (3.3.2) of Phase I.

3.7 Phase IV: Pilot scale system - Effect of plant density

3.7.1 Description of setup and design considerations – Phase IV

The experimental setup used in this phase is similar to that used in Phase III, as previously shown in Figure 8.

3.7.2 Operating conditions – Phase IV

The pilot scale system in Phase IV was run using synthetic greywater to investigate the effect of plant density of water hyacinth (selected from Phase II) on the treatment of synthetic greywater using the optimum hydraulic loading rate (obtained from Phase III). The initial plant densities used (wet mass basis) were 0, 0.803±0.066, 1.62±0.12, 2.37±0.155 and 4.34±0.242 kg/m^2, for Reactor 1, Reactor 2, Reactor 3, Reactor 4, and Reactor 5, respectively. To perform the experiments in Phase III, about 750 L of synthetic greywater was prepared on a daily basis to accommodate the daily flows needed for the five Reactors.

3.7.3 Sampling and sample analysis – Phase IV

A 500 ml sample was collected from the influent and the effluent of the Reactors. In addition, samples were collected from intermediate points between the influent and effluent of some Reactors and along the Reactor length. The influent sample consisted of a composite of the greywater entering each of the five Reactors. The samples were collected at a fixed hour of the day after 3, 5, 8, 12, 15 and 19 days from the start of the experiment. The collected samples were tested for pH, turbidity, TSS, DO, COD and BOD_5. The analytical procedures of testing were similar to that previously discussed in section (3.3.2) of Phase I.

3.7.4 Determination of evaporation/evapotranspiration and plant growth rates – Phase IV

Rate of evaporation in the control Reactor (R_1 – No plants) as well as rate of evaporation/evapotranspiration in the Reactors ($Q_{evp.}$) were calculated using the following equation:

$$Q_{evp.} = Q_{influent} - Q_{effluent}$$

Where:

$Q_{influent}$: The flow rate entering the Reactor

$Q_{effluent}$: The flow rate exiting the Reactor

Plant growth rate was measured every 3 days and maintained at the original plant density ($\pm$10%) in each Reactor, over the duration of the experiments in Phase IV (18 days). Excess plants were removed and additional plants were added (If needed) to reach the original set plant density in each planter bed Reactor. Air temperature was monitored using online weather forecasts and water temperature in each Reactor was recorded during each sampling event using a handheld thermometer. Influent and effluent flow rates were measured using a beaker and a timer.

3.8 Phase V: Pilot scale greywater treatment system - Real greywater

3.8.1 Pre-experiment - Sourcing and collection of real greywater in Phase V

A one-day sampling survey was conducted to assess the composition of real greywater that can be generated along one day from a residential facility in New Cairo. Samples were collected from the faculty housing of the AUC in New Cairo. The results of this pre-experiment allow the selection of the collection time during the day for the real greywater samples that will be used in the experiments of this phase. Nine samples were collected from the end point of the main stack that collects greywater from the hand basins, showers, kitchen sinks and washing machines of sixteen residential apartments in the faculty housing facility. The samples were collected at different hours during the time from 7:00 AM to 7:00 PM of the day of collection. The collected samples were tested for turbidity, TSS and COD. The analytical procedures of testing were similar to that previously discussed in section (3.3.2) of Phase I.

3.8.2 Description of setup and design considerations – Phase V

The experimental setup used in Phase V was similar to that used before in Phases III and IV. Figure 10 shows a schematic diagram of the experimental setup in this phase. As shown in Figure 10, two Reactors (R_1 and R_2) were used in the experiments of the current phase. One of the Reactors (R_1) was operated as control (without plant cover) while the other Reactor (R_2) was operated with plant cover.

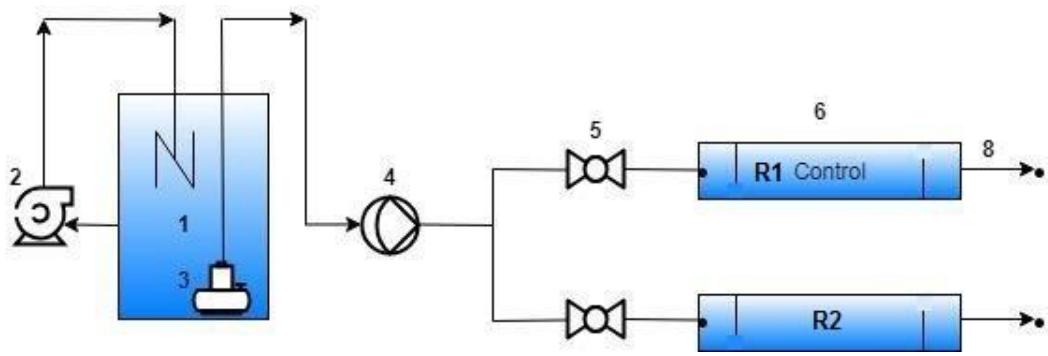


Figure 10: Schematic diagram of the experimental set-up in Phase V: 1) storage tank; 2) centrifugal pump; 3) submersible pump; 4) diaphragm pump; 5) flow control valves; 6) control and planter bed Reactor; 7) sampling points; 8) treated greywater effluents

3.8.3 Operating conditions – Phase V

The pilot scale system in Phase V was run using real greywater to study the performance of the aquatic filtration system in treating real greywater when using the optimum operating conditions obtained from Phase III and Phase IV, with regards to hydraulic loading rate and wet plant density. A total amount of 200 L of real greywater was collected whenever required to provide the necessary flow required for the daily operation of the system.

3.8.4 Sampling and sample analysis – Phase V

A 500 ml sample was collected from the influent and the effluent of each Reactor. The influent sample consisted of a composite of the greywater entering each of the two Reactors. The samples were collected at a fixed hour of the day after 3, 5, 8, 12, 15, 19, 22, 26 and 29 days from the start of the experiment. The analytical procedures of testing were similar to that previously discussed in section (3.3.2) of Phase I.

3.8.5. Determination of evaporation/evapotranspiration and plant growth rates – Phase V

Rate of evaporation in the control Reactor as well as rate of evaporation/evapotranspiration in the other Reactor ($Q_{evp.}$) were calculated using the following equation:

$$Q_{evp.} = Q_{influent} - Q_{effluent}$$

Where:

$Q_{influent}$: The flow rate entering the Reactor

$Q_{effluent}$: The flow rate exiting the Reactor

The initial plant wet density in Reactor 2 was 2.173 kg/m^2. Plant growth rate was measured every 3 days over the period of 30 days. Ambient air temperature was monitored using online weather forecasts and water temperature in each Reactor was recorded on each sampling event using a handheld thermometer. Influent and effluent flow rates were measured using a beaker and a timer.

CHAPTER 4: Results and Discussion

4.1 Phase I: Synthetic greywater preparation

4.1.1 Synthetic greywater formulation

As mentioned before in section (3.3.2) in Materials and Methods, synthetic greywater was prepared by mixing tab water with different chemicals that simulate the different contaminants commonly present in greywater. Therefore, trials with different mixtures were conducted to obtain the desired recipe for synthetic greywater. Table 13 shows the recipe of synthetic greywater that was used in the experimental works carried out in Phase II, III and IV.

Table 13: Recipe of synthetic greywater (current study)

Product	Function	PSD*							Contribution of material to pollution parameter	Conc. (g/l)
Sodium dodecyl sulfate	anionic surfactant			3			6	7	pH, COD, BOD_5, TDS, turbidity, NH_3-N, PO_4-	0.01
Sodium hydrogen carbonate	pH buffer				4				TDS, color, COD, BOD_5	0.075
Sodium Sulphate	viscosity control agent				4	5			TDS, color	0.05
Cellulose	suspended solids				4				COD, BOD_5, TSS	0.025
Lactic acid	acid produced by skin		2	3	4			7	pH, NH_3-N, PO_4-, COD, BOD_5	0.025 ml/l
Clay soil	suspended solids					5			TSS, color, turbidity	0.15
Septic effluent**	microbiological load					5			TSS, COD, BOD_5, FC	10 ml/l

*PSD: pollution stimulated is due to: (1) human body (2) shampoo and shower gel (3) soap (4) deodorant (5) tooth paste (6) shaving and moisturizing cream (7) make-up and make-up remover
**Septic effluent: wastewater effluent which is collected in an underground septic tank. It constitutes from faeces, urine and other waste matter that is made of harmless using bacteria

To determine the effect of each constituent on the BOD_5 content of the mixture, each constituent was mixed with 10 ml of septic effluent in 1 L of DI water. Then, BOD_5 was measured for each mixture (Table 14). Septic effluent is wastewater effluent which is collected in an underground septic tank. It constitutes from feces, urine and other waste matter that is made of harmless using bacteria and it was added to simulate microbiological load in the mixture.

Table 14: BOD_5 resulted from each constituent in the mixture

Chemical Substance	Conc.	BOD_5
Sodium Dodecyl Sulfate	1 g/l + 10 ml WW	84
Sodium Hydrogen Carbonate	1 g/l + 10 ml WW	20
Sodium Sulfate	1 g/l + 10 ml WW	15
Cellulose	1 g/l + 10 ml WW	81
lactic acid	1 ml/l + 10 ml WW	88
WW	10 ml/l WW	23

To stimulate turbidity and color in the mixture, yellow sand, course aggregate, fine aggregate and clay soil were tested separately. To select the suitable substance that could produce turbidity and color in the greywater mixture without affecting the values of other water quality parameters, 1 g of each substance was added to 500 ml tab water in a sterile beaker. All of the tested materials resulted in high turbidity and color (Table 15). However, clay soil was readily available in large quantities in the lab, which made it a viable option in the current study.

Table 15: Turbidity and color resulted from each constituent in the mixture

Parameter	Yellow sand	Course aggregate	Fine aggregate	Clay soil
Turbidity (NTU)	130	374	115	433
Color (ptCo)	524	> 550	> 550	> 550

4.1.2 Synthetic greywater composition

Table 16 and Table 17 summarize the minimum, maximum, average and median values for the different water quality parameters obtained from different research work on light and heavy greywater. From Table 16 and Table 17, it can be observed that the water quality parameters of the synthetic greywater stimulated in the current study are within the range of the values of water quality parameters reported in literature for light and heavy greywater. Therefore, the recipe obtained in this phase was used to simulate real greywater and was used to generate the greywater that was used in conducting the experiments of the next phases of this study (Phases II, III and IV).

Table 16: Summary of characteristics of light greywater from different countries

Parameter	Unit	Literature				Current Study
		LGW Min	LGW Max	LGW Avg.	Median	
PH	-	6.4	8.1	7.26	7.3	7.49
TSS	mg/l	29	505	122.35	61.1	93
Turbidity	NTU	12.6	375	88.33	40.8	25
COD	mg/l	55	633	223.50	176.2	103
BOD_5	mg/l	20	300	115.86	93.0	69
Ammonia (NH_3/NH_4+)	mg/l	0.1	15	4.44	4.2	2.46
NO_3-	mg/l	0	28.7	6.32	2.9	1.6
PO_4^{-3}	mg/l	0.5	1.3	0.95	0.95	5.2
Fecal Coliform	CFU/100 ml	0.1	3.42E+05	93728.11	1735.0	NC

Christova-Boal et al. (1996); (Lin et al., 2005); (Kim et al., 2007): (Chaillou et al., 2011); (Nolde, 2000); (Pidou et al., 2007) and (Winward et al., 2008); (March et al., 2004); (Merz et al., 2007); (Prathapar et al., 2005)

Table 17: Summary of characteristics of heavy greywater from different countries

Parameter	Unit	Literature				Current Study
		HGW Min	HGW Max	HGW Avg.	Median	
PH	-	6.35	10	7.78	7.6	7.49
TSS	mg/l	12	315	127.85	112.5	93
Turbidity	NTU	19	254	101.91	51.9	25
COD	mg/l	50	2568	634.04	267.5	103
BOD_5	mg/l	48	1056	356.84	179.9	69
Ammonia (NH_3/NH_4+)	mg/l	0.1	75	19.91	1.8	2.46
NO_3-	mg/l	0.05	25.8	5.47	0.6	1.6
PO_4^{-3}	mg/l	1.52	9.8	5.95	5.6	5.2
Fecal Coliform	CFU/100 ml	3.57E+03	5.40E+06	1268683.89	35200.0	NC

Christova-Boal et al. (1996); (Itayama et al., 2006); (Kim et al., 2009): (Mandal et al., 2011); (Paulo et al., 2009); (Elmitwalli and Otterpohl, 2007); (Scheumann et al., 2007); (Halalsheh et al., 2008); (Prathapar et al., 2005)

4.2 Phase II: Lab scale greywater treatment system

In this phase, different aquatic plants were used to investigate the effectiveness of treating synthetic greywater compared to a control (no plant condition). Water hyacinth, papyrus reed and common reed were selected to run the planter bed Reactors. The Reactors were operated for a period of 19 days and a total of 6 sampling events were collected to evaluate the performance of the system.

4.2.1 Performance of different plant types in treating synthetic greywater

Table 18 shows the effect of using synthetic sponge on the removal of several water quality parameters of synthetic greywater. Table 19, Table 20, Table 21 and Table 22 also show the change of concentration of different water quality parameters of synthetic greywater when using control (no plant condition), water hyacinth, papyrus reed and common reed, respectively.

It can be demonstrated from Table 18 that the synthetic sponge played an important role in reducing color up to 35.6%, turbidity up to 36% and TSS up to 50%. The significant reduction in the aforementioned water quality parameters can be attributed to the settlement of some of the suspended solids in the bottom of the filter bed and the entrapment of others in the synthetic sponge. Overall, all of the planter bed Reactors were effective in the removal of FC, NH3-N and PO4. However, Table 20 shows that water hyacinth was the most effective in the removal of COD and NH_3-N compared to the other two aquatic plant species. Common reed, on the other hand, was the most effective in the removal of turbidity, color, TSS, PO_4-, BOD_5 and FC. Finally, papyrus reed was the most effective in the removal of TDS. It was also observed that water hyacinth was able to remove a total mass of 83 mg TDS (45% higher than the control sample), 0.5 mg PO_4- (60% higher than the control sample), 53 mg COD (5.7% higher than the control sample) and 572 mg FC (44% higher than the control sample). The variable change in the organic matter content as well as TSS, turbidity and color in all of the planter bed Reactors throughout the experiment can be attributed to the particulates released by the plants and microbial biodegradation of them.

Table 18: Effect of synthetic sponge treatment on physico-chemical characteristics of synthetic greywater in Phase II

Parameter	Raw Greywater	Greywater after Synthetic Sponge Treatment
pH	7.98	7.8
Turbidity (NTU)	36	23
Color (ptCo)	194	125
TSS (mg/l)	104	52
TDS (mg/l)	335	300
NH_3-N (mg/l)	1.26	1.24
PO_4- (mg/l)	2.8	2.7
COD (mg/l)	131	110
BOD_5 (mg/l)	25	20
Fecal coliform (CFU/100ml)	1000	950

Table 19: Change of control sample concentration with time in Phase II

Control Sample							
Parameter	Inlet Greywater	2 days	5 days	8 days	13 days	16 days	19 days
pH	7.8	8.16	7.47	7.94	8.03	8.23	6.44
Turbidity (NTU)	23	23	17	15	19	17	21
Color (ptCo)	125	131	100	110	129	80	124
TSS (mg/l)	52	51	48	36	45	67	71
TDS (mg/l)	300	280	293	277	290	271	255
NH_3-N (mg/l)	1.24	-	-	0.18	-	-	0.18
PO_4- (mg/l)	2.7	-	-	1.9	-	-	2.5
COD (mg/l)	110	-	57	58	-	15	60
BOD_5 (mg/l)	20	-	-	11	-	-	12
Fecal coliform (CFU/100ml)	950	-	-	-	1800	-	630

Table 20: Effect of aquatic treatment with water hyacinth on physico-chemical characteristics of synthetic greywater in Phase II

Water Hyacinth							
Parameter	Inlet Greywater	2 days	5 days	8 days	13 days	16 days	19 days
pH	7.8	7.83	7.41	7.28	7.66	7.97	5.95
Turbidity (NTU)	23	12	19	15	26	27	34
Color (ptCo)	125	75	114	92	156	162	210
TSS (mg/l)	52	18	54	50	21	49	69
TDS (mg/l)	300	280	270	261	240	230	217
NH_3-N (mg/l)	1.24	-	-	0.24	-	-	0.19
PO_4- (mg/l)	2.7	-	-	1.6	-	-	2.2
COD (mg/l)	110	-	176	28	-	57	57
BOD_5 (mg/l)	20	-	-	5	-	-	13
Fecal coliform (CFU/100ml)	950	-	-	-	210	-	378

Table 21: Effect of aquatic treatment with common reed on physico-chemical characteristics of synthetic greywater in Phase II

Common Reed							
Parameter	Inlet Greywater	2 days	5 days	8 days	13 days	16 days	19 days
pH	7.8	7.66	7.2	7.22	7.16	7.43	6
Turbidity (NTU)	23	12	10	13	30	15	21
Color (ptCo)	125	67	58	114	155	91	113
TSS (mg/l)	52	-	74	94	121	15	95
TDS (mg/l)	300	287	334	302	239	245	207
NH_3-N (mg/l)	1.24	-	-	0.22	-	-	0.24
PO_4- (mg/l)	2.7	-	-	1.4	-	-	1.8
COD (mg/l)	110	75	30	18	-	45	185
BOD_5 (mg/l)	20	-	-	-	-	-	31
Fecal coliform (CFU/100ml)	950	-	-	-	195	-	30

Table 22: Effect of aquatic treatment with papyrus reed on physico-chemical characteristics of synthetic greywater in Phase II

Papyrus Reed							
Parameter	Inlet Greywater	2 days	5 days	8 days	13 days	16 days	19 days
pH	7.8	7.54	7.21	7.03	7.3	7.37	6.07
Turbidity (NTU)	23	40	41	39	46	31	70
Color (ptCo)	125	240	221	231	227	176	387
TSS (mg/l)	52	100	127	170	125	157	227
TDS (mg/l)	300	293	213	175	109	135	138
NH_3-N (mg/l)	1.24	-	-	0.32	-	-	0.26
PO_4- (mg/l)	2.7	-	-	5.5	-	-	6.9
COD (mg/l)	110	45	60	-	-	114	108
BOD_5 (mg/l)	20	-	-	-	-	-	18
Fecal coliform (CFU/100ml)	950	-	-	-	200	-	50

4.2.2 Plant growth and evaporation/evapotranspiration from the system

Evaporation/evapotranspiration from each planter bed Reactor as well as the control bed have been realized on every sampling event, as shown in Table 23. It can be demonstrated that over the 19 days of experiment, water hyacinth has achieved the lowest greywater evaporation rate with a total of 0.114 liter of water per kg of plant wet mass per day (l/kg.d). On the other hand, common reed has achieved the highest rate of evaporation with a total of 0.497 l/kg.d followed by papyrus reed with a total of 0.483 l/kg.d. The high evaporation rate in the common reed and papyrus reed can be attributed to the far-reaching leaf system that increases the surface area from which water is evapotranspirated.

The average air temperature recorded in the greenhouse during the experiments of Phase II was 28±2.7. While, the water temperature (T_{water}) recorded in all planter bed Reactors were very comparable with an average value of 26±2.7 ^{o}C.

Table 24 shows the plant mass at the beginning and the end of the experiments. It can be observed from Table 24 that common reed and papyrus reed have started to experience fatigue signs indicated by the yellow color, as opposed to water hyacinth which flourished at the end of the experiment. Stress signs experienced can be attributed to the lack of nutrients (nitrogen and phosphorus) present in the receiving medium (synthetic greywater).

Table 23: Total amount of water evaporated from all planter bed Reactors throughout the experiment in Phase II

Parameter	2 days	2-5 days	5-8 days	8-13 days	13-16 days	16-19 days	Total amount evaporated throughout the whole experiment
Control Sample							
Amount of water evaporated (L)	0.2	0.6	0.6	0.5	1.15	1	4.05
Water Hyacinth							
Amount of water evaporated (L)	0.3	0.8	0.8	1.3	0.92	1	5.12
Common Reed							
Amount of water evaporated (L)	1.2	3	3.5	6	3.6	5	22.3
Papyrus Reed							
Amount of water evaporated (L)	1.6	4	4.4	6	2.65	3	21.65

Table 24: Photos of plants at the start and the end of the batch experiment in Phase II

Plant Name	Start of Experiment	End of Experiment
Control (No plants)		
Water Hyacinth		

Papyrus Reed		
Common Reed		

4.2.3 Plant selection for conducting Phases III, IV and V

Based on the results obtained in Phase II, water hyacinth and common reed showed better performance compared to papyrus reed. However, water hyacinth showed less stress signs compared to common reed. Also, water hyacinth proved to lose less water through evaporation/evapotranspiration compared to common reed and papyrus reed. Moreover, water hyacinth is a floating aquatic plant species and therefore it's considered much easier in management, including planting and harvesting compared to common reed. For all the aforementioned reasons, water hyacinth was selected to carry out the remaining phases of the study.

4.3 Phase III: Pilot scale system - Effect of hydraulic loading rate

In this phase, the effect of different hydraulic loading rates on the treatment performance of synthetic greywater was investigated using a pilot scale aquatic filtration system that utilizes similar wet densities of water hyacinth (selected from Phase II). The constructed greywater treatment system was operated for a period of 20 days and a total of 5 sampling events were conducted to evaluate the performance of the system.

4.3.1 Change of water quality parameters concentration with time and distance travelled in Reactors

It can be demonstrated from Figure 11 that as time passes, there has been no significant change in the effluent value of pH in all Reactors. It can also be observed that turbidity, color, TSS, COD and BOD_5 gradually decreased with time in all Reactors, however Reactor 5 (HLR = 0.29 $m^3/m^2/d$) was able to achieve the highest removal of all pollution parameters. Figure 11 also shows that the concentration of different parameters, except pH, decreased with the decrease in HLR.

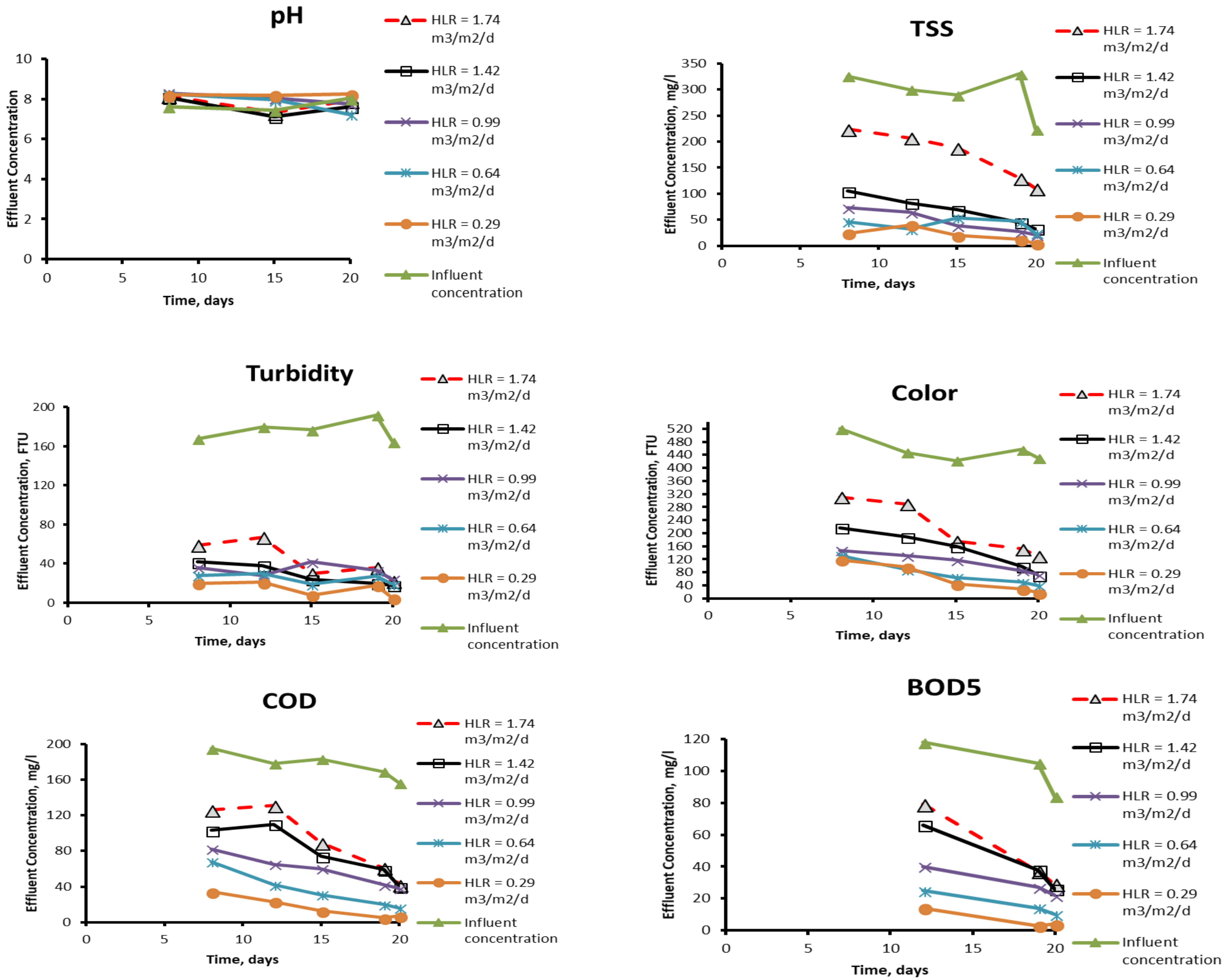


Figure 11: Change of concentration of different water quality parameters with time in Phase III

The removal of TSS from greywater in the Reactors can be attributed to settling of some of the suspended particles to the bottom of the Reactor and the entrapment of others in the root zone of water hyacinth. BOD_5 and COD can be removed through biodegradation of some of the organic matter attached to the root zone of the plant as well as the settling of the settleable suspended fractions of COD and BOD_5 (Vipat et al, 2008).

Figure 12, Figure 13, Figure 14 and Figure 15 show that there has been significant reduction in turbidity, TSS, COD and BOD_5 at distance 0.2375 m from the inlet of Reactors 1 and 5 after 15, 19 and 20 days from the start of the experiment. However, the change in concentration of the aforementioned water quality parameters was insignificant for the rest of the intermediate sampling points taken along Reactors 1 and 5 which can be attributed to the relatively small Reactor's length.

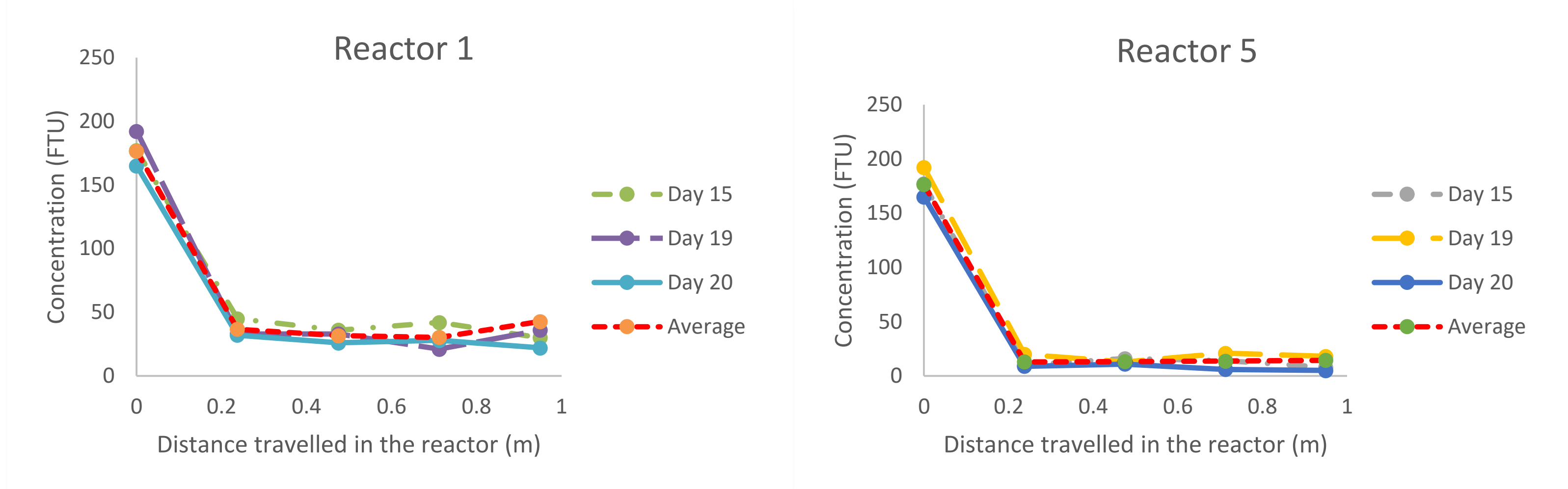


Figure 12: Change of turbidity with distance travelled in Reactor 1 and 5 in Phase III

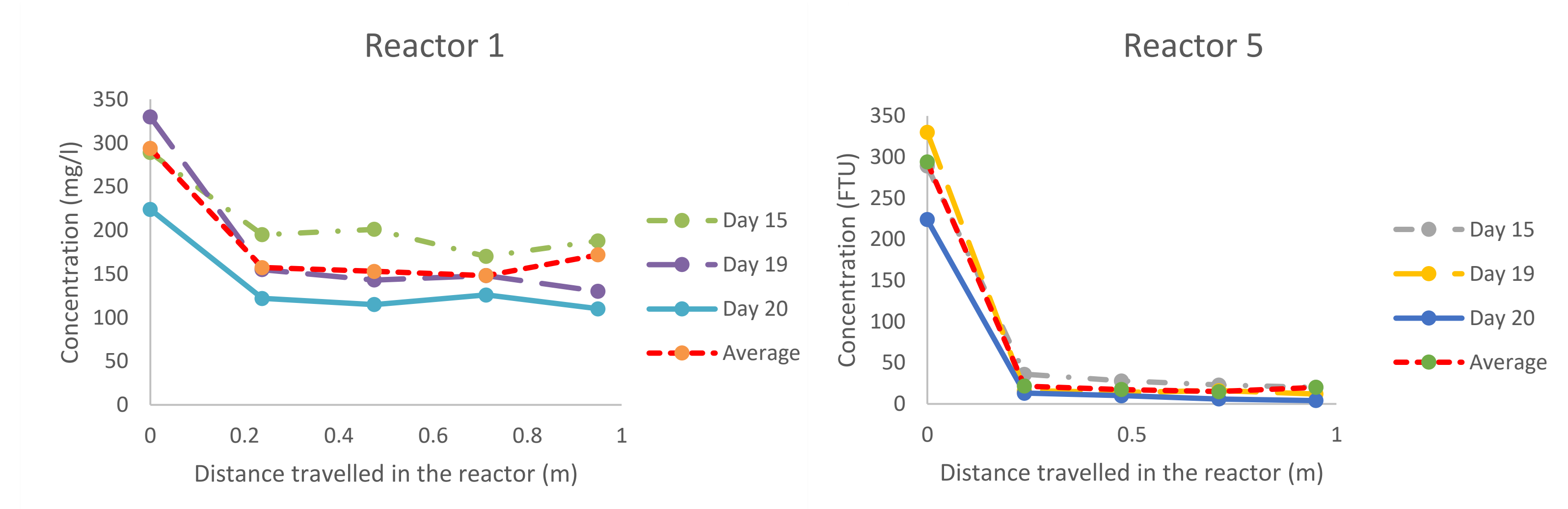


Figure 13: Change of TSS with distance travelled in Reactor 1 and 5 in Phase III

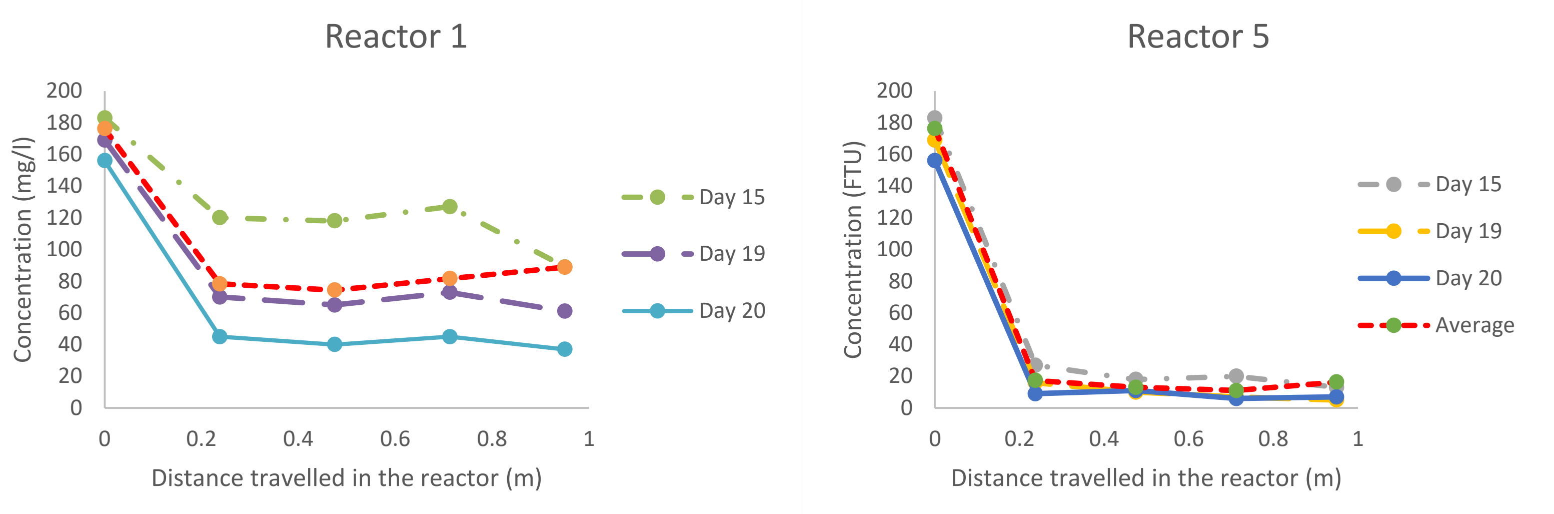


Figure 14: Change of COD with distance travelled in Reactor 1 and 5 in Phase III

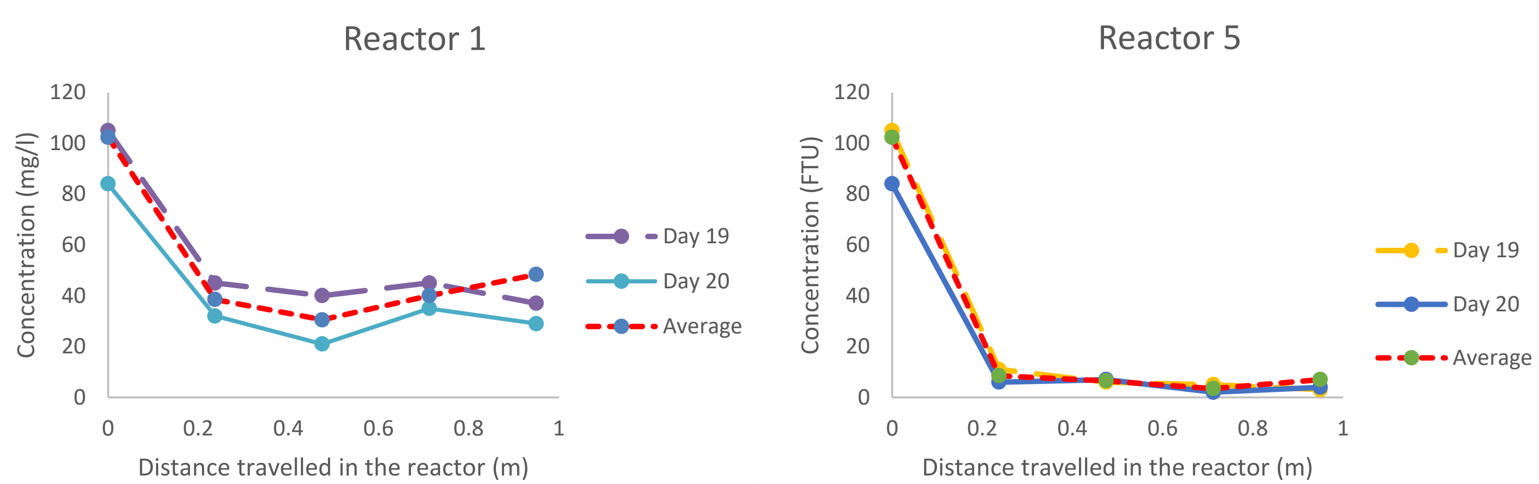


Figure 15: Change of BOD_5 with distance travelled in Reactor 1 and 5 in Phase III

4.3.2 Effect of hydraulic loading rate on effluent quality

Figure 16 shows the effect of hydraulic loading rate on turbidity, TSS, BOD_5 and COD. Each data point in the figure represents the average concentration of the parameter throughout the experiment. From Figure 16, it can be observed that the best performance can be obtained at the lowest HLR (0.29 $m^3/m^2/d$). The effluent concentration of the different pollution parameters increases with the increase in HLR to 1.74 $m^3/m^2/d$. Water hyacinth in Reactor 5 (HLR = 0.29 $m^3/m^2/d$) was able to reduce the turbidity of greywater from 176 NTU to 14 NTU$\pm$7 NTU (on average basis). TSS also went down in Reactor 5 from an average of 294 mg/l to 20 mg/l$\pm$13.5 mg/l. Moreover, COD experienced noticeable reduction in Reactor 5 where it decreased from average of 176 mg/l to 16 mg/l$\pm$12 mg/l. Finally, BOD_5 in Reactor 5 reduced from an average of 102 mg/l to 7 mg/l$\pm$6 mg/l. Figure 16 also shows that the operation of the treatment system at HLR of 0.29 $m^3/m^2/d$ results in an effluent organic quality (BOD_5 and COD) that complies with the limits reported in the Egyptian Code of Practice for Reuse in Irrigation; Category A (501-2015).

It is believed that high detention times in Reactors of lower HLR are responsible for better removal of TSS, turbidity and as a result, removal of COD and BOD_5 fractions associated with them. Also, high Hydraulic Retention Time (HRT) implies lower loading rate and more contact time with the plant root zone which in turn results in high microbial degradation and sorption thereby resulting in higher removal efficiency of pollutants. COD and BOD_5 removal efficiency is a function of HRT. The longer HRT increases the interaction within the aquatic plant system, which results in higher organic matter (Kanabkaew and Puetpaiboon, 2004).

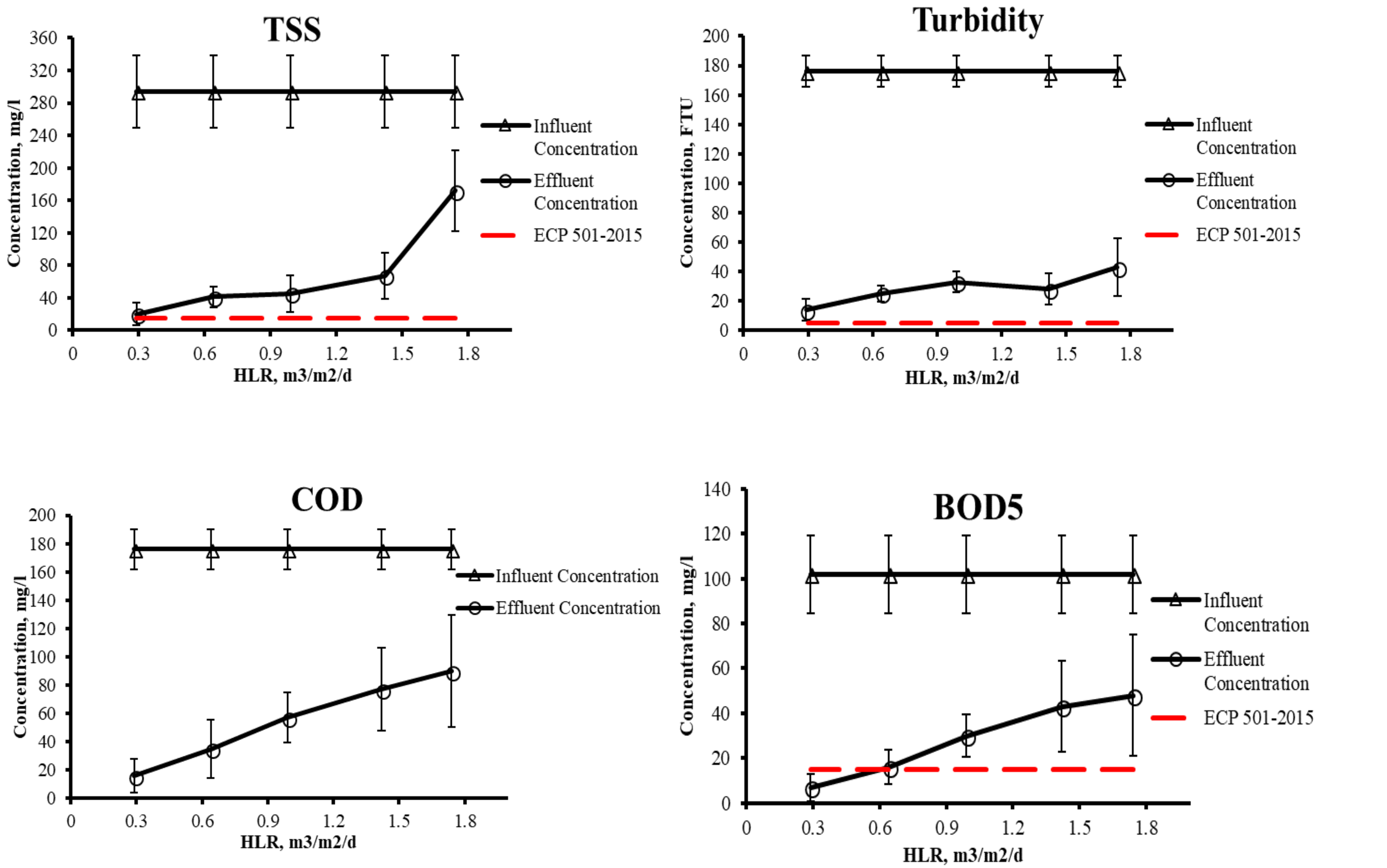


Figure 16: Change of concentration of different water quality parameters with HLR in Phase III

4.3.3 Removal Efficiency

The average removal efficiency values for all water quality parameters over the period of 20 days have been presented for the five Reactors in Figure 17. It can be demonstrated that as HLR decreases, there has been gradual improvement in the average removal efficiency of turbidity, color, TSS, NO_3-N, PO_4-, COD and BOD_5. However, Reactor 5 (HLR = 0.29 $m^3/m^2/d$) recorded the best treatment performance with an average removal efficiency of 91.9 % for turbidity, 87% for color, 93.4% for TSS, 76.5% for NO_3-N, 75.8% for PO_4-, 91% for COD and 93.5 for BOD_5.

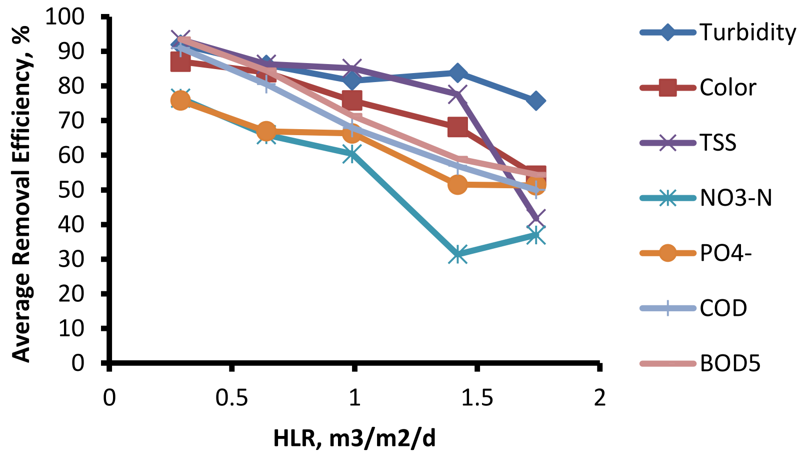


Figure 17: Average removal efficiency for different HLR in Phase III

4.3.4 Plant growth and evaporation/evapotranspiration from the system

The cumulative rate of evaporation in all Reactors can be shown in Figure 18. It can be observed from Figure 18 that the rate of water loss in all Reactors throughout the experiment is almost the same with an average value of 9 ml/min except for Reactor 1 (HLR = 1,74 m^3/m^2d) which recorded a slightly higher water loss with an average value of 13 ml/min. Hence, there is no significant difference between the different Reactors with regards to water lost through evaporation/evapotranspiration.

The average air temperature recorded during the experiments of Phase III was 20.4±1.67. While, the average water temperature (T_{water}) recorded in Reactor 1, Reactor 2, Reactor 3, Reactor 4 and Reactor 5 were 21.28±0.93 °C, 21.24±0.75 °C, 20.78±0.46 °C, 20.52±0.6 °C and 21.1±0.74 °C, respectively. These temperatures are considered within the favorable range of temperature that supports water hyacinth growth. (Reddy, Sutton and Bowes, 1983)

Table 25 shows the average plant growth in all Reactors. It can be observed from Table 25 that the average plant growth rate in Reactor 1, Reactor 2, Reactor 3, Reactor 4 and Reactor 5 were 0.02±0.21, 0.024±0.174, 0.008±0.18, 0.005±0.22 and 0.008±0.23 kg/d, respectively. The high rate of evaporation, as well as the rapid growth of water hyacinth biomass can be attributed to the continuous supply of nutrients to the plants from their medium (synthetic greywater). In addition, the ambient temperatures during the day supports the plant growth.

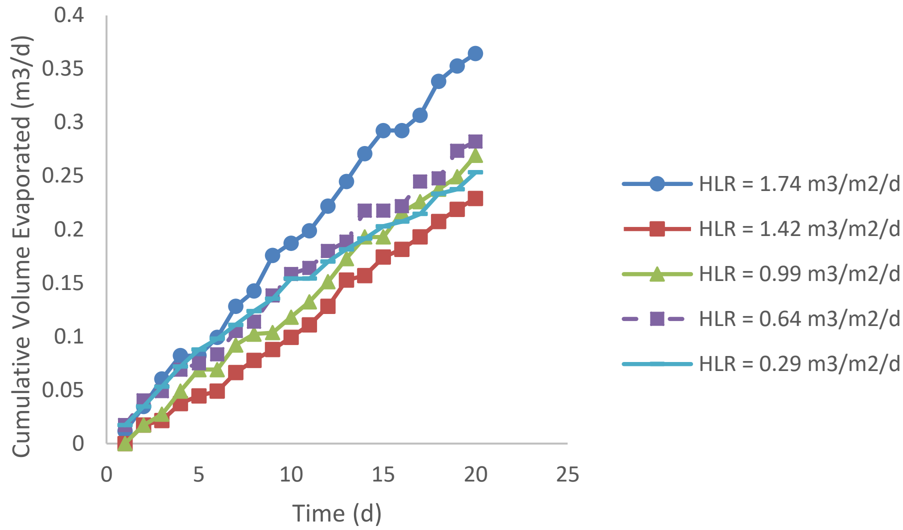


Figure 18: Cumulative volume of water lost through evaporation/evapotranspiration at different HLR in Phase III

Table 25: Average plant growth at different HLR in Phase III

Parameter	3 d	6 d	9 d	12 d	15 d	18 d	Average plant growth (kg/d)	STDev.
Reactor #1 (HLR = 1.74 $m^3/m^2/d$)								
Measured plant mass (kg)	2.14	1.53	2.27	1.62	1.56	1.74		
Corrected plant mass (kg) (+-10%)	1.31	1.53	1.35	1.33	1.4	1.33		
Plants removed (kg)	0.83	0	0.92	0.29	0.16	0.41	**0.02**	**0.21**
Reactor #2 (HLR = 1.42 $m^3/m^2/d$)								
Measured plant mass (kg)	2.08	1.61	2.16	1.58	1.62	1.8		
Corrected plant mass (kg) (+-10%)	1.33	1.48	1.33	1.35	1.46	1.3		
Plants removed (kg)	0.75	0.13	0.83	0.23	0.16	0.5	**0.024**	**0.174**
Reactor #3 (HLR = 0.99 $m^3/m^2/d$)								
Measured plant mass (kg)	2.05	1.78	2.32	1.52	1.52	1.52		
Corrected plant mass (kg) (+-10%)	1.3	1.48	1.31	1.31	1.37	1.32		
Plants removed (kg)	0.75	0.3	1.01	0.21	0.15	0.2	**0.008**	**0.18**
Reactor #4 (HLR = 0.64 $m^3/m^2/d$)								
Measured plant mass (kg)	2.19	1.51	2.2	1.43	1.43	1.47		
Corrected plant mass (kg) (+-10%)	1.31	1.51	1.34	1.34	1.32	1.35		
Plants removed (kg)	0.88	0	0.86	0.09	0.11	0.12	**0.005**	**0.22**

Reactor #5 (HLR = 0.29 $m^3/m^2/d$)								
Measured plant mass (kg)	2.17	1.47	2.4	1.71	1.67	1.52		
Corrected plant mass (kg) (+-10%)	1.34	1.47	1.33	1.45	1.3	1.36		
Plants removed (kg)	0.83	0	1.07	0.26	0.37	0.16	**0.008**	**0.23**

4.3.5 Effect of Hydraulic Shock Loading – Phase III

The average effluent quality for the samples collected from Reactor 4 (HLR = 0.64 $m^3/m^2/d$, plant density = 1.448 kg/m^2) and Reactor 5 (HLR = 0.29 $m^3/m^2/d$, plant density = 1.448 kg/m^2) at different hours of the day can be shown in Table 26 and Table 27. It can be exhibited from the conducted experiment that there has been initial treatment of synthetic greywater in both Reactors, thought Reactor 5 has resulted in better removal of suspended solids and organic matter over the one day experiment with a turbidity removal rate of 68.4%, TSS removal rate of 54.1%, COD removal rate of 39.8% for the first four hours and a removal efficiency of 86.8%, 63.9% and 80.6%, respectively for the next twenty hours, as opposed to Reactor 4 which recorded a turbidity removal rate of 50.6%, TSS removal rate of 31.5%, COD removal rate of 29.6% for the first four hours and a removal efficiency of 75.3%, 55.4% and 73.5%, respectively for the next twenty hours. However, better hydraulic shock loading response can be attained using a combination of better Reactor design, hydraulic flow rate and plant density.

Table 26: Hydraulic shock loading effect on different quality parameters for Reactor 4 in Phase III

Reactor 4 (HLR = 0.64 $m^3/m^2/d$, plant density = 1.448 kg/m^2)										
Reactor condition	**Influent Water Quality**	**Before shock loading**	**During shock loading**				**After shock loading**		
Time (h)		0	1	2	3	4	8	12	24
Q (ml/min)		130	400				130		
		Effluent Water Quality							
Turbidity (NTU)	165	19	95	80	42	86	72	65	43
TSS (mg/l)	224	24	235	222	189	209	177	159	136
COD (mg/l)	156	16	189	175	151	138	121	84	52

Table 27: Hydraulic shock loading effect on different quality parameters for Reactor 5 in Phase III

Reactor 5 (HLR = 0.29 $m^3/m^2/d$, plant density = 1.448 kg/m^2)									
Reactor condition	**Influent Water Quality**	**Before shock loading**	**During shock loading**				**After shock loading**		
Time (h)		0	1	2	3	4	8	12	24
Q (ml/min)		60	180				60		
		Effluent Water Quality							
Turbidity (NTU)	165	5	63	78	81	55	35	28	23
TSS (mg/l)	224	4	210	175	161	140	132	120	110
COD (mg/l)	156	7	162	157	144	118	95	61	38

4.3.6 Kinetics of removal of COD and BOD_5 – Phase III

Removal of COD and BOD_5 in a free water surface flow system can be expressed with the first order removal kinetics in a plug flow Reactor, as shown in Equation (1).

$$C/C_o = \exp(-K_t * t) \text{ ----------------- } (1)$$

Where,

C = Effluent concentration of the water quality parameter, mg/L

C_o = Influent concentration of the water quality parameter, mg/L

K_t = Temperature-dependent first-order reaction rate constant

t = Hydraulic residence time, d

Q = Average flow rate through the system, m^3/d

d = Depth of submergence, m

As = Surface area of the system in plain view, m^2

Equation (1) can be rearranged as follows:

$$\ln C - \ln C_o = -K_t * [(As * d)/Q] \text{ ---------------- } (2)$$

Where the surface area (As) is calculated according to Equation (3):

$$As = L*W \text{ ----------------- } (3)$$

Where,

L = bed length, m

W = bed width, m

To obtain the rate of removal constants for COD and BOD_5 in the plug flow system that is sued for greywater treatment in the current study. Equation (2) was plotted for the collected data in Phase III. Figure 19 and Figure 20 show the change in ln C/C_o with time for the COD and BOD_5 obtained from Phase III using synthetic greywater.

The regression analysis of the data in Figure 19 and Figure 20 revealed that the first order kinetic equation that is used to estimate the effluent concentrations of COD and BOD_5 can be expressed in Equation (4) and Equation (5), respectively, as follows:

$$\text{COD: } C/C_o = e^{-1.556 * (As*d/Q)} \text{ --------------- (4)}$$

$$BOD_5\text{: } C/Co = e^{-1.916 * (As*d/Q)} \text{ --------------- (5)}$$

The reaction rate constant of most biological reactions is directly related to the reaction temperature and increases with an increase in temperature, or vice versa (Atkins and De Paula, 2006). As water temperatures vary from day to day throughout the 20 days of experiment, the micro-organisms acclimatize to different types and quantities of nutrients available in their medium and plant activity varies accordingly. Thus, it is expected that the rate constants will change as well. Hence, the values obtained here should be treated as a point of reference

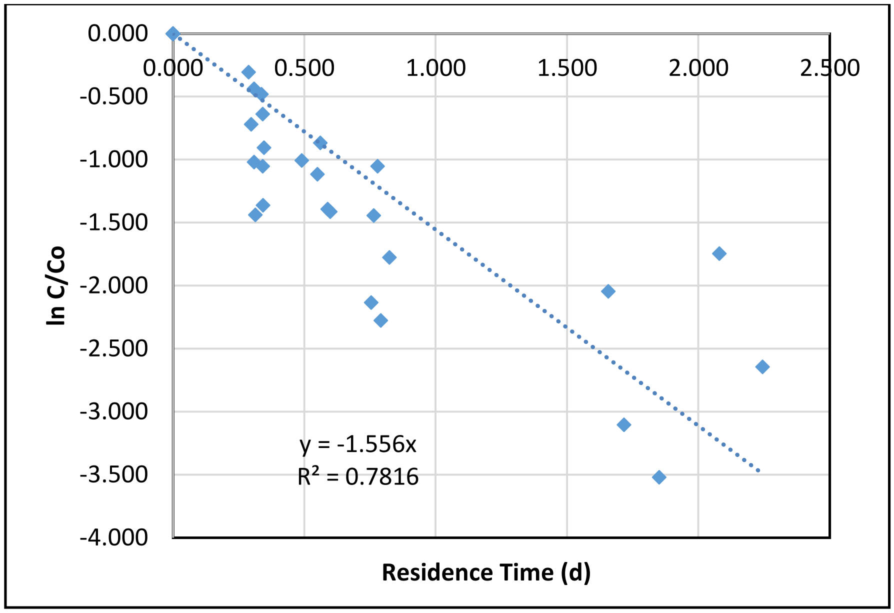


Figure 19: Kinetics of removal of COD in Phase III

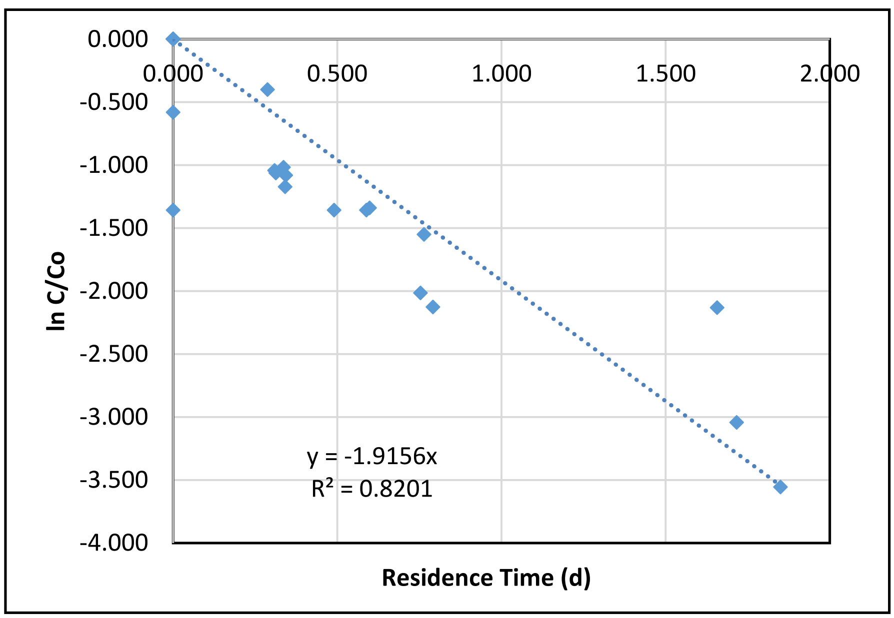


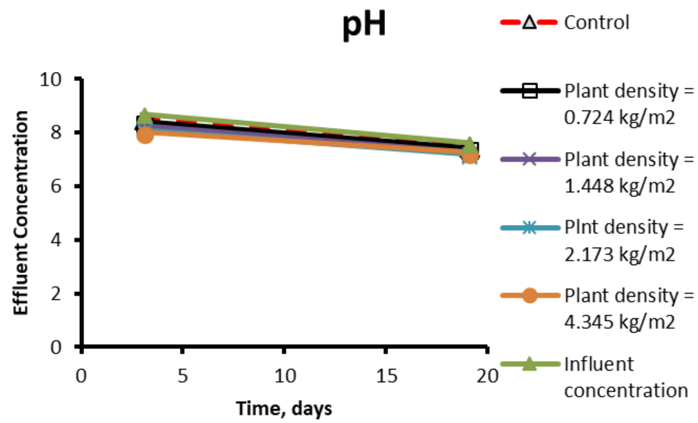
Figure 20: Kinetics of removal of BOD_5 in Phase III

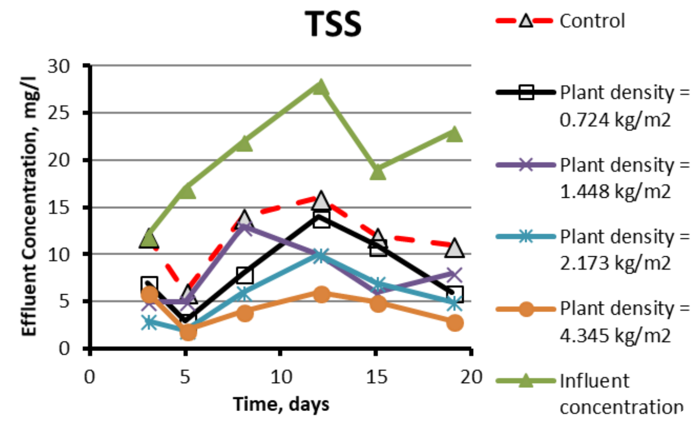
4.4 Phase IV: Pilot scale greywater treatment system - Effect of plant density

In this phase, the effect of different wet densities of water hyacinth on the treatment of synthetic greywater was investigated using a pilot scale aquatic filtration system that utilizes similar hydraulic loading rates (selected from Phase III). The constructed greywater treatment system was operated for a period of 19 days and a total of 6 sampling events were conducted to evaluate the performance of the system.

4.4.1 Change of water quality parameters concentration with time

It can be demonstrated from Figure 21 that as time passes, there has been no significant change in the effluent value of pH in all Reactors. It can also be observed that turbidity, TSS, COD and BOD_5 gradually decreased with time in all Reactors, however Reactor 4 Reactor 5 with plant density of 2.173 kg/m^2 and 4.345 kg/m^2, respectively were able to achieve the highest removal of all pollution parameters. Figure 21 also shows that the concentration of different parameters, except pH, decreased with the increase in plant wet density.





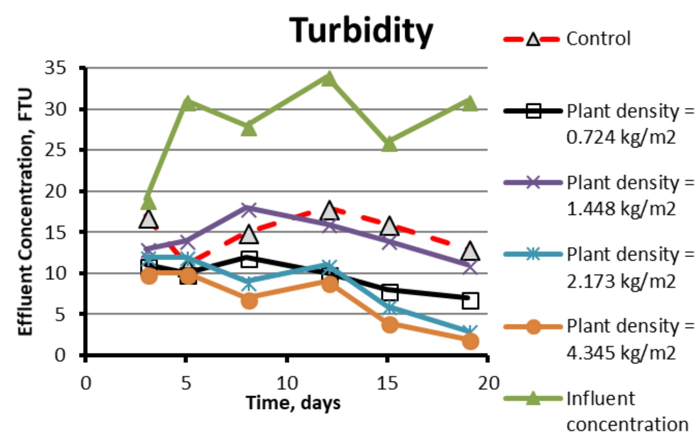
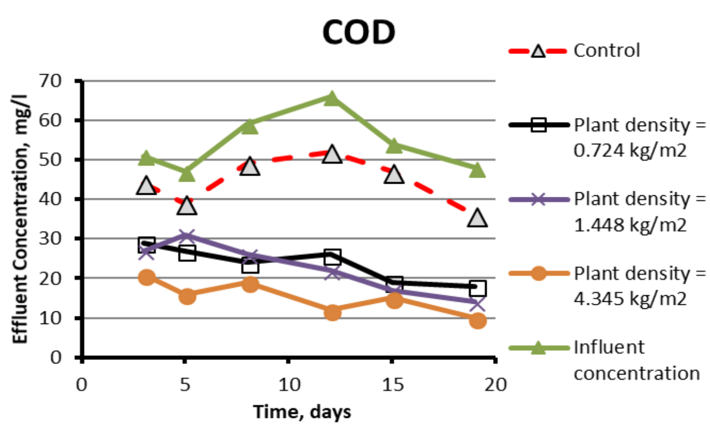
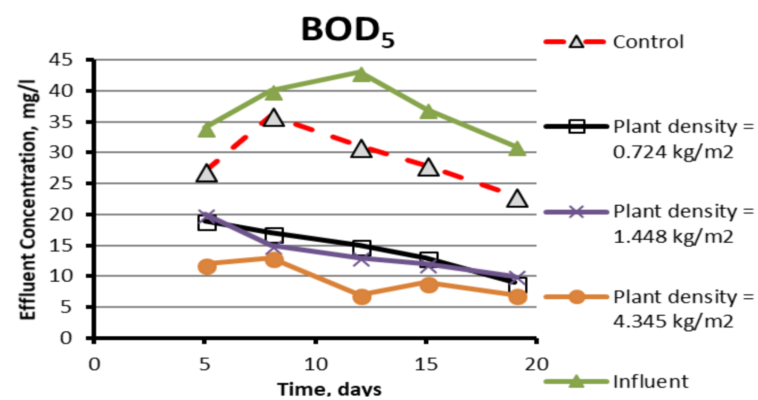


Figure 21: Change of concentration of different water quality parameters with time in Phase IV





4.4.2 Effect of plant density on effluent quality

Figure 22 shows the effect of plant density on turbidity, TSS, BOD_5 and COD. Each data point in the figure represents the average concentration of the parameter throughout the experiment. From Figure 22, it can be observed that the best performance can be obtained at the highest wet plant density (4.345 kg/m^2). Water hyacinth in Reactor 5 (Wet density = 4.345 kg/m^2) was able to reduce the turbidity of greywater from 28 NTU to 7 NTU$\pm$3.3 (on average basis). TSS also went down in Reactor 5 from an average of 20 mg/l to 4 mg/l$\pm$1.7 mg/l. Moreover, COD experienced noticeable reduction in Reactor 5 where it decreased from average of 54 mg/l to 16 mg/l$\pm$4.1 mg/l. Finally, BOD_5 in Reactor 5 reduced from an average of 37 mg/l to 10 mg/l$\pm$2.8 mg/l. Water hyacinth in Reactor 4 (Wet density = 2.173 kg/m^2) was also able to reduce the turbidity and TSS of greywater from an average of 28 NTU to 10 NTU$\pm$3.7 and from 20 mg/l to 5.5 mg/l$\pm$2.9 mg/l, respectively.

Figure 22 also shows that the operation of the treatment system at wet plant density of 4.345 kg/m^2 and 2.173 kg/m^2 results in an effluent organic quality (BOD_5 and COD) that complies with the limits reported in the Egyptian Code of Practice for Reuse in Irrigation; Category A (501-2015).

Figure 22 shows that the higher the water hyacinth plant density, the more aerobic bacteria attached to the plant surface area which is used to decompose organic matter present in synthetic greywater which is reflected in reasonable decrease of COD and BOD_5. Also, the higher the plant density, the more root biomass used for the entrapment of suspended solids which is reflected in better treatment of TSS and turbidity.

Zhu *et al*. (2011) studied the growth characteristics, plant aboveground and belowground biomass of seven wetland plants. They suggested that a greater ratio of plant biomass to wetland volume can enhance the contact between plant roots and wastewater resulting in a greater nutrient removal. Similar conclusion was reached by Sushil (2012) and Lu *et al*. (2012).

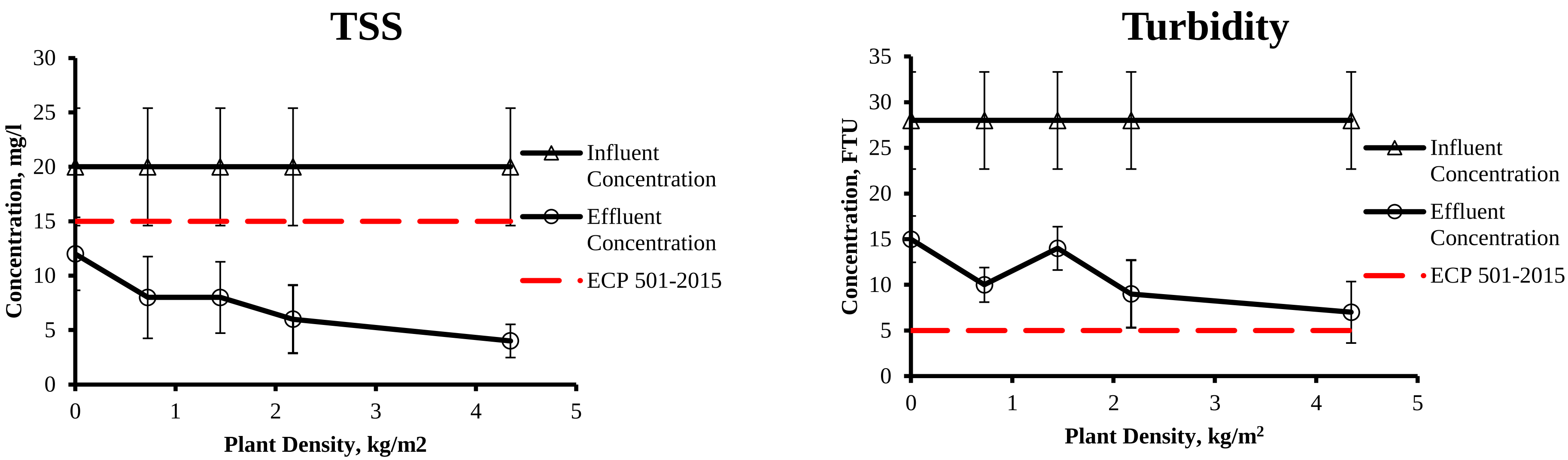
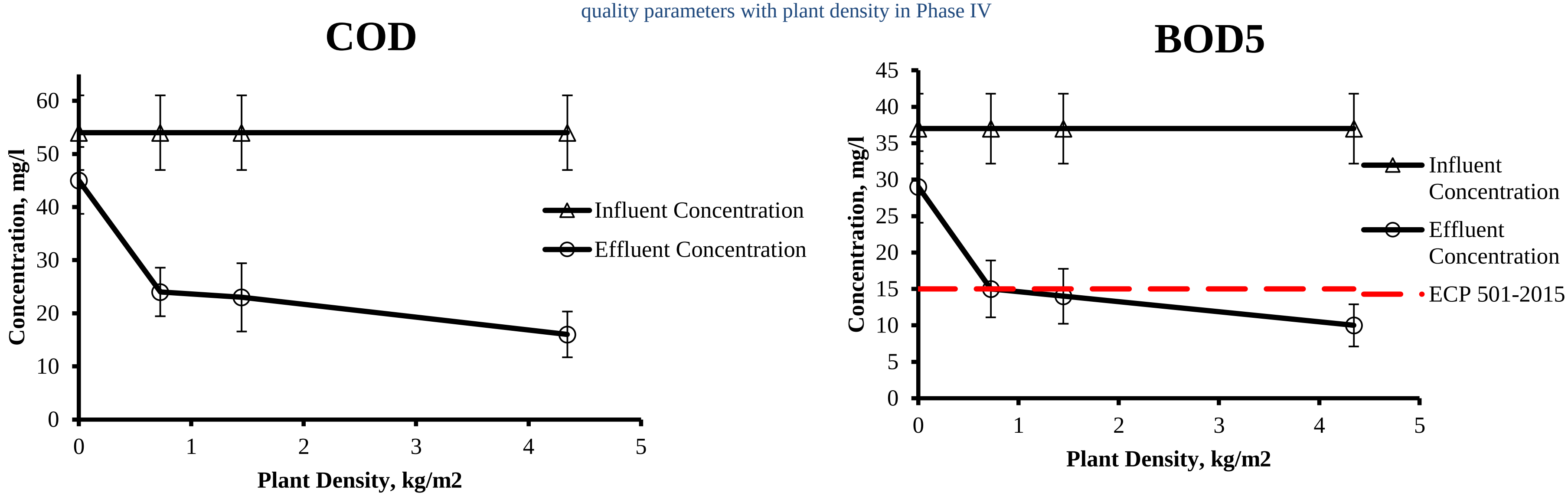


Figure 22: Change of concentration of different water quality parameters with plant density in Phase IV



4.4.3 Removal Efficiency

The average removal efficiency values for all water quality parameters over the period of 19 days have been presented for the four Reactors as well as the control Reactor in Figure 23. It can be demonstrated that as wet plant density increases, there has been gradual improvement in the average removal efficiency of turbidity, TSS, COD and BOD_5. However, Reactor 5 (Plant density = 4.345 kg/m^2) recorded the best treatment performance with average removal efficiency of 73.6 % for turbidity, 76.5% for TSS, 71% for COD and 73.8% for BOD_5. Reactor 4 (Plant density = 2.173 kg/m^2) also recorded the second-best treatment performance with average removal efficiency of 67% for turbidity and 74% for TSS.

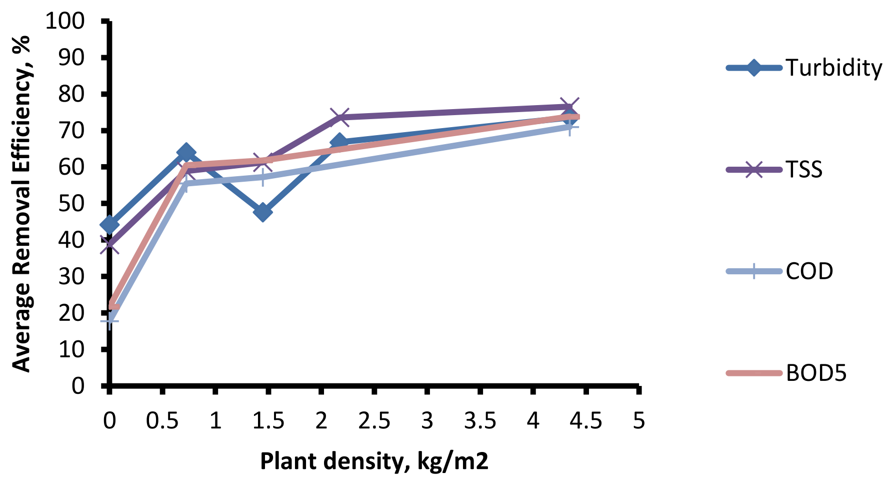


Figure 23: Average removal efficiency for different plant densities in Phase IV

4.4.4 Evaporation losses from the system

The cumulative rate of evaporation in all Reactors can be shown in Figure 24. It can be observed from Figure 24 that Reactor 5 (Plant density = 4.345 kg/m^2) recorded the highest cumulative evaporation rate due to the increased biomass that led to a higher evaporation rate from their surface area. Table 28 also shows the average plant growth in all Reactors. It can be observed from Table 28 that the average plant growth rate in Reactor 2, Reactor 3, Reactor 4 and Reactor 5 were 0.0044$\pm$0.022, 0.017$\pm$0.04 kg/d, 0.018$\pm$0.084 and 0.014$\pm$0.14, respectively.

The average air temperature recorded during the experiments of Phase IV was 17.3$\pm$0.52. While, the average water temperature (T_{water}) recorded in Reactor 1, Reactor 2, Reactor 3, Reactor 4 and Reactor 5 were 17.7$\pm$0.87 ^oC, 17.8$\pm$0.78 ^oC, 17.7$\pm$1.1 ^oC, 17.7$\pm$1.1 ^oC and 18.25$\pm$0.79 ^oC, respectively. These temperatures are considered within the favorable range of temperature that supports water hyacinth growth. (Reddy, Sutton and Bowes, 1983)

For an aquatic filtration system to work efficiently, optimal plant growth is the key parameter. Many environmental factors can influence plant growth and its performance, such as temperature, pH, solar radiation, and salinity of the water. The mass and size of aquatic plants are a function of these factors (USEPA, 1988). Nutrient availability also affects the growth and performance of aquatic plants. As per Makhanu (1997) it comprises of 95% water and 5% dry matter, out of which silica, potassium, nitrogen and protein is 50%, 30%, 15% and 5%, respectively.

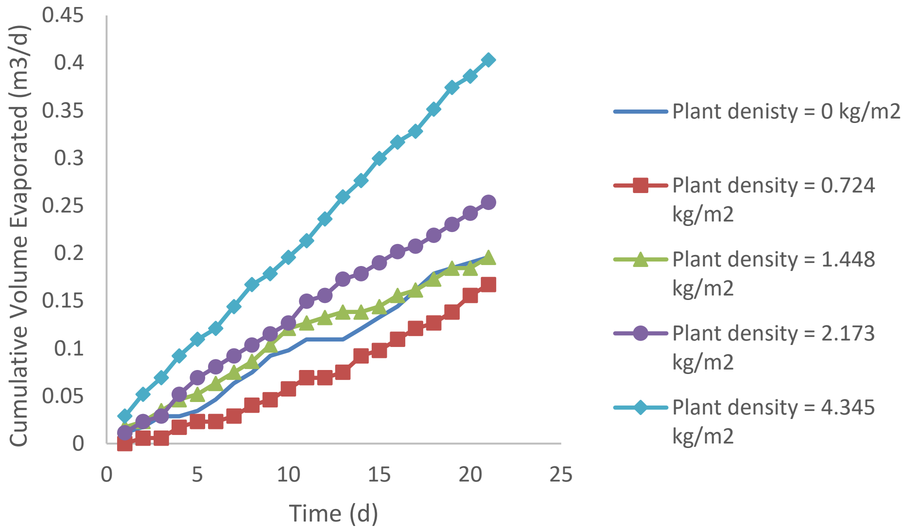


Figure 24: Cumulative volume of water lost through evaporation/evapotranspiration at different plant wet densities in Phase IV

Table 28: Average plant growth for different wet plant densities in Phase IV

Parameter	**3 d**	**6 d**	**9 d**	**12 d**	**15 d**	**18 d**	**Average plant growth (kg/d)**	**STDev.**
Reactor #2 (Plant density = 0.74 kg/m^2)								
Measured plant mass (kg)	0.76	0.872	0.851	0.846	0.838	0.768		
Corrected plant mass (kg) (+-10%)	0.696	0.684	0.682	0.692	0.685	0.689		
Plants removed (kg)	0.064	0.188	0.169	0.154	0.153	0.079	**0.0044**	**0.022**
Reactor #3 (Plant density = 1.448 kg/m^2)								
Measured plant mass (kg)	1.6	1.67	1.58	1.71	1.723	1.684		
Corrected plant mass (kg) (+-10%)	1.372	1.378	1.378	1.381	1.384	1.413		
Plants removed (kg)	0.228	0.292	0.202	0.329	0.339	0.271	**0.017**	**0.04**
Reactor #4 (Plant density = 2.173 kg/m2)								
Measured plant mass (kg)	2.566	2.312	2.422	2.41	2.435	2.386		
Corrected plant mass (kg) (+-10%)	2.084	2.062	2.071	2.069	2.088	2.075		
Plants removed (kg)	0.482	0.25	0.351	0.341	0.347	0.311	**0.018**	**0.084**
Reactor #5 (Plant density = 4.345 kg/m2)								
Measured plant mass (kg)	4.878	4.31	4.225	4.416	4.496	4.386		
Corrected plant mass (kg) (+-10%)	4.152	4.168	4.136	4.23	4.246	4.134		
Plants removed (kg)	0.726	0.142	0.089	0.186	0.25	0.252	**0.014**	**0.144**

4.5 Phase V: Pilot scale greywater treatment system – Real greywater

In this phase, the performance of the aquatic filtration system in treating real greywater when using the optimum operating conditions obtained from Phase III and Phase IV was investigated. The greywater treatment system was operated for a period of 29 days and a total of 9 sampling events were conducted to evaluate the performance of the system.

Before conducting the experiments, a survey was performed to investigate the time of availability and characteristics of greywater at a potential source of real greywater in the Faculty Housing at AUC. To conduct this survey, 9 samples were collected and analyzed for turbidity, TSS and COD, in a time duration that starts at 7:00 AM and ends at 7:00 PM. Table 29 shows the concentration of these parameters in the collected real greywater samples at the allocated times.

As shown in Table 29, the characteristics of greywater varied significantly among the different time slots. However, greywater was readily available for collection in the time duration from 8:00 AM to 12:00 PM. Also, the quality of greywater collected in the aforementioned time duration closely represented light synthetic greywater used in running Phases III and IV. Therefore, it was decided to collect 200 l/d of real greywater generated from 8:00 AM to 12:00 PM to run the phases of the current experiment.

Table 29: Concentration of different quality parameters of real greywater collected at different time slots

Parameter	S1* (7:20 AM) **	S2 (8:00 AM)	S3 (8:30 AM)	S4 (12:00 PM)	S5 (12:30 PM)	S6 (1:00 PM)	S7 (5:00 PM)	S8 (6:00 PM)	S9 (7:00 PM)
Turbidity (NTU)	233	104	94	96	119	111	87	74	55
TSS (mg/l)	28	67	51	42	38	18	37	27	19
COD (mg/l)	1168	494	469	497	664	642	384	399	337

* S = samples

** ( ) = time of collection

4.5.1 Performance of the system in the treatment of real greywater at optimum design/operating condition

It can be demonstrated from Figure 25 and Figure 26 that as time passes, there has been no significant change in the effluent value of pH in Reactor 2 which was operated at wet plant density of (2.173 kg/m^2) and HLR of (0.29 $m^3/m^2/d$). On the other hand, turbidity, TSS, NH_3- N, NO_3-N, PO_4^-, COD and BOD_5 gradually decreased with time.

It can be inferred that water hyacinth in Reactor 2 was able to reduce the turbidity of greywater from 82 NTU to 54 NTU$\pm$20 NTU (on average basis). TSS also went down from an average of 52 mg/l to 34 mg/l$\pm$24 mg/l. Moreover, COD experienced noticeable reduction over the duration of experiment, where it decreased from average of 366 mg/l to 217 mg/l$\pm$71 mg/l. Finally, BOD_5 reduced from an average of 222 mg/l to 129 mg/l$\pm$43 mg/l.

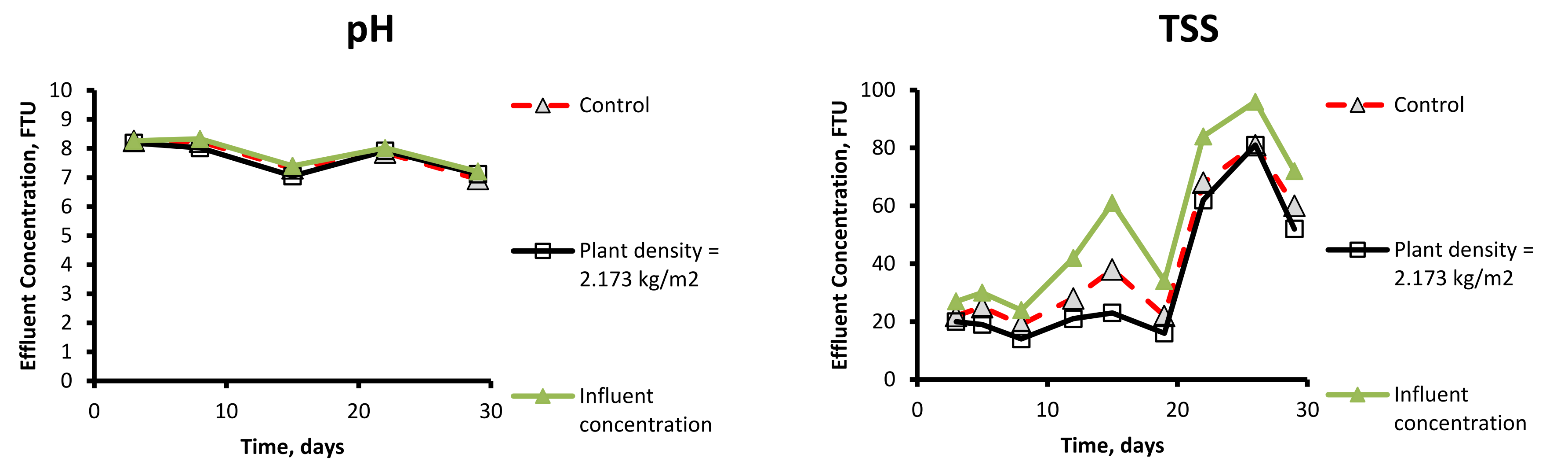
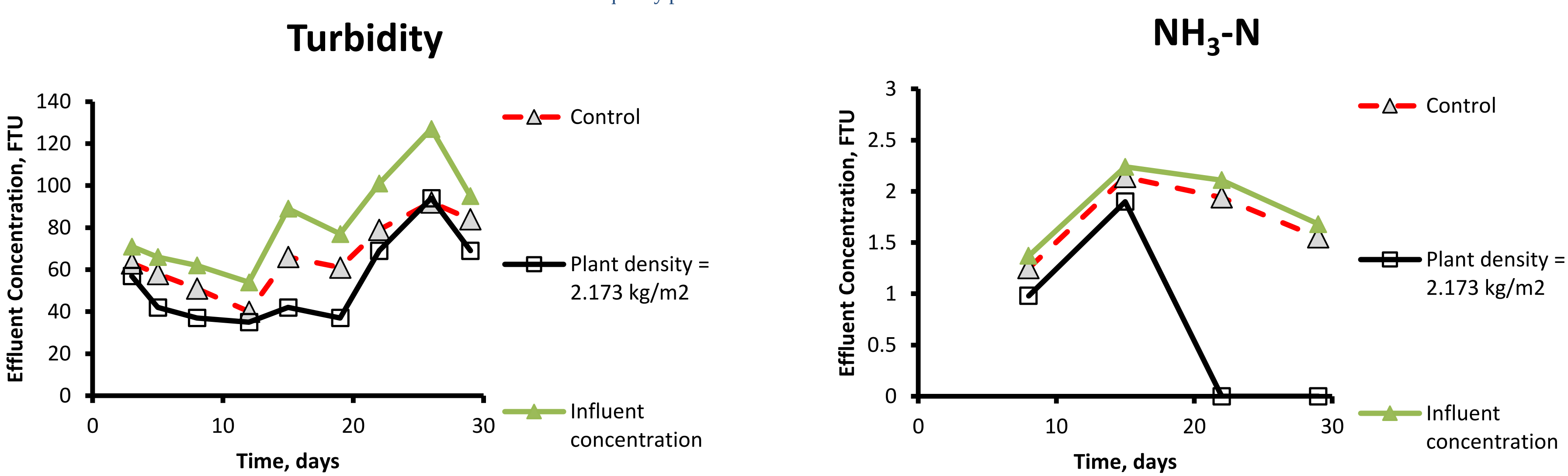


Figure 25: Change of concentration of different water quality parameters with time in Phase V



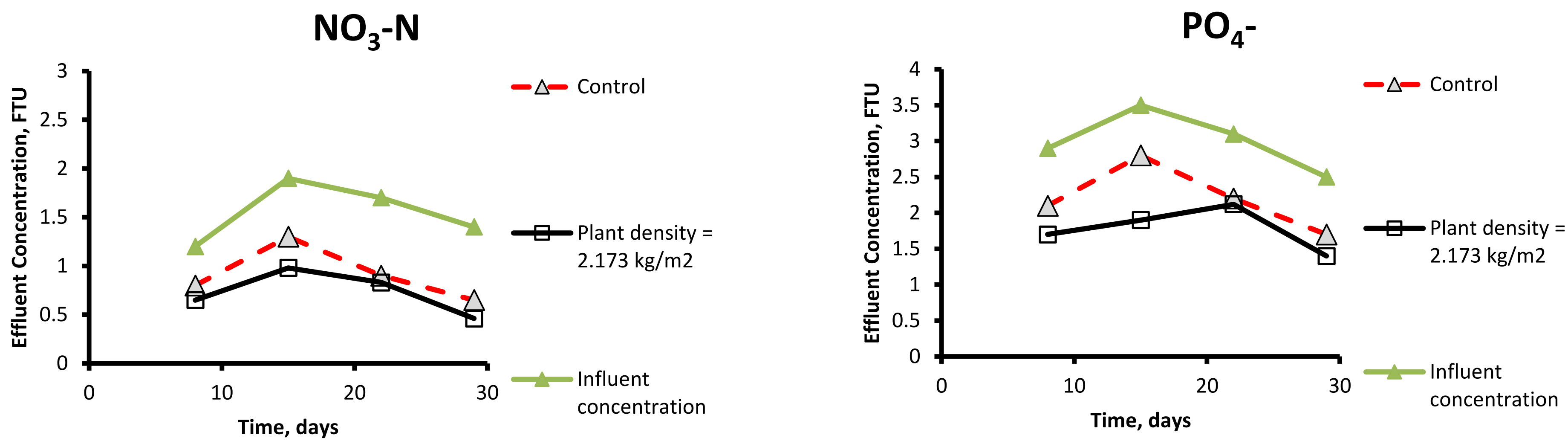
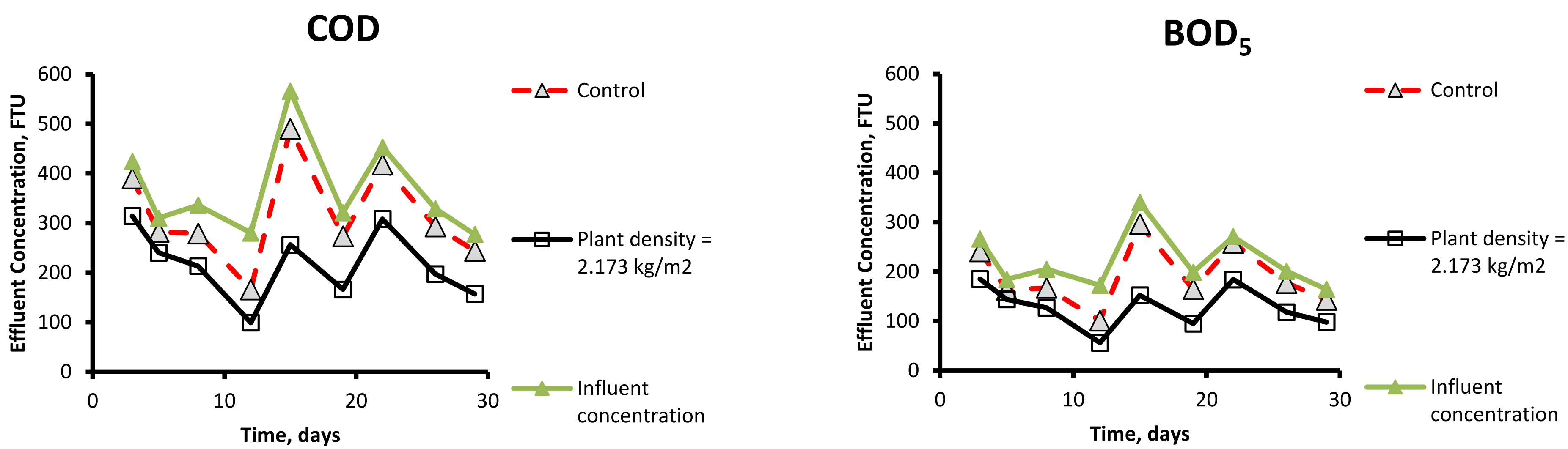


Figure 26: Change of concentration of different water quality parameters with time in Phase V



4.5.2 Plant growth and evaporation/evapotranspiration from the system

The cumulative rate of evaporation in the two Reactors can be shown in Figure 27. Reactor 2 (with plant cover) recorded an average rate of water loss of 7.44 ml/min throughout the duration of the experiment. Table 30 shows that the average plant growth rate in Reactor 2 was 0.787$\pm$0.05 kg/d.

The average air temperature recorded during the experiments of Phase V was 16.4$\pm$3.4. While, the average water temperature (T_{water}) recorded in Reactor 1 and Reactor 2 were 13.6$\pm$0.92 ^oC and 13.7$\pm$0.32 ^oC, respectively. These temperatures are considered within the favorable range of temperature that supports water hyacinth growth. (Reddy, Sutton and Bowes, 1983)

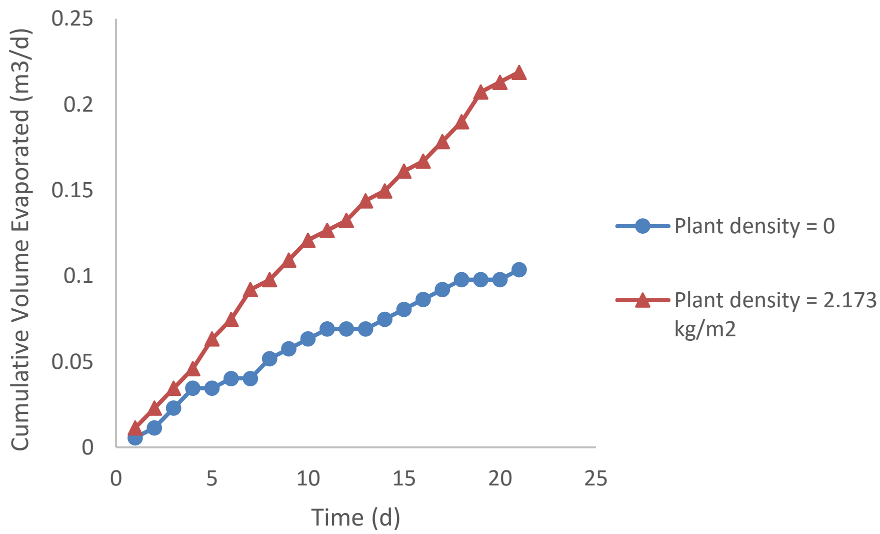


Figure 27: Cumulative volume of water lost through evaporation/evapotranspiration at different plant wet densities in Phase V

Table 30: Average plant growth in Reactor 2 in Phase V

Parameter	3 d	6 d	9 d	12 d	15 d	18 d	21 d	24 d	27 d	30 d	Average plant growth (kg/d)	STDev.
Reactor #2 (Plant mass = 2.173 kg/m^2)												
Measured plant mass (kg)	2.138	2.211	2.275	2.311	2.352	2.411	2.465	2.513	2.561	2.613	**0.787**	**0.05**

4.6 Economic Vision

Economic studies should be carried out to investigate the use of greywater at the community level to reduce the overall cost. There are two main variables to consider when designing and constructing a pilot scale aquatic filtration system:

4.6.1 Cost

- Mechanical pumping of raw greywater from the house into the storage tank and from the storage tank to the onsite greywater treatment system
- Transferring plants to the greywater treatment system
- Pumping treated greywater to its end use
- Labor cost required to run the system (1 worker, 2 h/d)
- Electricity associated with operation of the system (pump and mixer)
- Maintenance cost (periodic harvesting of the plants and removal of accumulated sediments from the bottom of the reactor)

4.6.2 Savings

- Less strain on sewage treatment plants (Less treatment cost, energy consumption and greenhouse gas emissions)
- Reduced potable water purchases
- Reduced water consumption for landscape irrigation

4.6.3 Case study

For the purpose of demonstrating a real-life economic study, a brief outline of the financial cost associated with constructing, running and maintaining the pilot scale aquatic filtration system used in this study on the level of an apartment building and a high-end compound has been attempted in this section.

Assumptions

- Total potable water consumption in an Egyptian household in a high end community = 300 L/capita.d (Egyptian Code of Practice, 2015)
- Total wastewater generated = 80% - 90% of the total potable water consumption (Egyptian Code of Practice, 2015)
- The average water use in the Egyptian household comprises 20% for shower and bath (Ministry of Water resources and irrigation,1997)
- A typical apartment building constitutes of a total of 5 floors, 2 apartment/floor, 5 capita/apartment
- A typical residential compound constitutes of 10 apartment buildings (3 floors, 2 apartment/floor, 4 capita/apartment) and 20 villas (6 capita/villa)
- Greywater will reside in the collection tank for 10 minutes
- Hydraulic loading rate entering and exiting the aquatic filtration reactor = 0.29 $m^3/m^2/d$ (Evaporation losses from the system have been ignored)

Calculations

➢ Apartment building

- $Q_{avg.}$ (potable water) = total capita * total water consumption = 50 capita * 300 L/capita.d = 15,000 L/d
- Qavg. (total wastewater) = 85% * 15,000 L/d = 12,750 L/d
- $Q_{avg.}$ (greywater) = 20% * 12,750 L/d = 2,550 L/d = 2.6 m^3/d
- Area of the reactor = Q/HLR = 2.6 (m^3/d)/0.29 ($m^3/m^2/d$) = 9 m^2
- Volume of the collection tank = 0.002 m^3/min * 10 min = 0.02 m^3

- Residential compound

  - $Q_{avg.}$ (potable water) = total capita * total water consumption = 360 capita * 300 L/capita.d = 108,000 L/d
  - Qavg. (total wastewater) = 85% * 108,000 L/d = 91,800 L/d
  - $Q_{avg.}$ (greywater) = 20% * 91,800 L/d = 18,360 L/d = 18 m^3/d
  - Area of the reactor = Q/HLR = 18 (m^3/d)/0.29 (m^3/m^2/d) = 62 m^2
  - Volume of the collection tank = 0.0125 m^3/min * 10 min = 0.125 m^3

Cost analysis

- Apartment building

  - 2 diaphragm pumps (0.1 m^3/h) = 7,000 Egyptian Pound (EP)
  - 1 submersible mixer (10 L/s) = 15,000 EP
  - 2 PVC tanks (0.5 m^3) = 2,000 EP
  - 1 PVC aquatic filtration tank (9 m^2) = 3,000 EP

  Total construction cost = 540 EP/capita (In addition to the cost associated with the operation and maintenance of the system)

- Residential compound

  - 2 diaphragm pumps (0.75 m^3/h) = 7,000 Egyptian Pound (EP)
  - 1 submersible mixer (10 L/s) = 15,000 EP
  - 2 PVC tanks (0.5 m^3) = 2,000 EP
  - 7 PVC aquatic filtration tank (9 m^2) = 21,000 EP

  Total construction cost = 125 EP/capita (In addition to the cost associated with the operation and maintenance of the system)

CHAPTER 5: CONCLUSIONS AND FUTURE RESEARCH

5.1 Conclusions

The physico-chemical parameters of the synthetic greywater used in our study was found comparable to that of real greywater sourced from previous publications in literature despite the high variability in raw real greywater composition.

As far as removal efficiencies are concerned, common reed was found most effective in treating organic and suspended pollutants, compared to water hyacinth and papyrus reed. However, the planting cost, removal operation and overall management is considered favorable to water hyacinth over the other two plant species. It was also concluded that over the duration of the experiment in Phase II, water hyacinth has achieved the lowest normalized greywater evapotranspiration rate which is considered an advantage for large surface areas in arid regions where the greywater medium is subject to high evaporation losses. Moreover, water hyacinth has shown minimal stress signs over the duration of the experiment when subjected to synthetic greywater, compared to the other two plant species.

It was concluded from the experiments of Phase III that water hyacinth-based systems operated at relatively low hydraulic loading rates (long HRTs) can remove large amounts of suspended solids and organic matter from synthetic greywater with overall removal efficiencies that can go up to of 91.9 % for turbidity, 87% for color, 93.4% for TSS, 76.5% for NO_3-N, 75.8% for PO_4-, 91% for COD and 93.5% for BOD_5. It was also concluded that in long HRTs Reactors, air temperature and influent contaminant concentrations had insignificant effect on the daily fluctuations in effluent BOD_5, COD, turbidity and TSS.

It was concluded from the experiments of Phase IV that water hyacinth-based systems operated at relatively high wet plant densities can remove large amounts of suspended solids and organic matter from synthetic greywater with overall removal efficiencies that can go up to 6.2% for pH, 66.8 % for turbidity and 73.6% for TSS.

It was concluded by the end of the experiments of Phases III and IV that the Reactor which operated at the lowest HLR (0.29 $m^3/m^2/d$) and highest wet plant density (2.173 kg/m^2) was able to achieve the desired treatment of synthetic greywater as per the Egyptian Code for Effluent Quality for Reuse in Landscape Irrigation (2015) for turbidity, TSS and BOD_5. It was also able to withstand hydraulic shock loading for 24 hours with overall removal efficiencies that can go up to 68.4% for turbidity, 54.1% for TSS and 39.8% for COD, for the first four hours and 86.8%, 63.9% and 80.6%, respectively for the next twenty hours. The differences in water hyacinth performance in the treatment of greywater between the present study and the previous studies could be attributed to the differences in system design, climate, and behavior of plants in the different geographical provinces and concentration of the pollutants in the greywater.

It was concluded from the experiments of Phase V that there was consistent decrease in turbidity, TSS, NH_3-N, NO_3-N, PO_4-, COD and BOD_5, despite the high variation in influent real greywater quality from day to day. Thus, the validation of this synthetic effluent by comparison with real greywater demonstrates that the designed and constructed aquatic filtration system using water hyacinth is a promising, low-cost, low-tech greywater treatment system that can be run and maintained by unskilled operators.

5.2 Future Research

The improvement in treatment in the Water Hyacinth based system is of particular significance considering the strict effluent quality standards recently imposed by the Egyptian Code of Practice. By dealing with real greywater, variation in the strength of the wastewater characteristics is expected as affected by the consumer habits. Future studies may study the effect of a pilot scale aquatic filtration system on the treatment performance of diluted greywater (Eg. 50% of raw greywater and 50% of fresh water).

When the kitchen outflow water is included in greywater, a relatively high amount of oil and grease is expected. Hence, the incorporation of a pre-filter/ settling tank could enhance the removal efficiency of the suspended solids and organic matter present in greywater before entering the aquatic filtration system. Also, the addition of effective microorganism (EM) to the raw greywater could enhance the settling and aeration processes effectively.

Furthermore, the installation of a dual layer of sand and gravel could be used as a pretreatment/post-treatment measure to enhance the overall quality of the effluent to the permissible level of 1st group (i.e. advanced treated water) as unrestricted water reuse in landscape irrigation according to the ‘‘Egyptian Guideline’’.

The study suggests that water hyacinth possess high biomass production and nutrients removal, while the water hyacinth decaying biomass can be used as a soil amendment to increase the nutrient and water-holding capacity of the soil in agriculture. Large amounts of detritus accumulated in the roots of floating water hyacinth mats suggest the need for periodic plant harvests to increasing the efficiency of pollutant removal through adsorption. On the other hand, further research on the life time expectancy of a single batch of water hyacinth before it loses its ability to treat greywater could be conducted.

Future studies may also consider the effect of continuous flow, long term aquatic filtration (this experiment was run in a relatively short span of time), and/or differing operating conditions. For example, an increased contact time between plants and water, higher water hyacinth biomass or incorporation of continuous flow in series rather than in parallel are parameters that may be explored.

Aquatic bed Reactors construction, operation and in turn performance could be improved by further acquisition of initial technical background as well as hydraulic and kinetic investigation on the topic. Hence, sampling should be conducted from multiple locations throughout the aquatic bed and integrated into long-term operation. In addition, future studies should include bacteriological counts to verify the magnitude of the health risk associated with reusing treated greywater in agriculture.

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