Contribution to the Development of Sustainable Sanitation in Emerging Countries

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M.Sc.

Samir Y. S. Alnahhal

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Promotionsausschuss:

Vorsitzender:	Prof. Dr.-Ing. Holger Kohl
Gutachter:	Prof. Dr.-Ing. Günther Seliger
Gutachter:	Prof. Dr.-Ing. Samir Afifi
Gutachterin:	Prof. Dr.-Ing. Vera Susanna Rotter

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Dedication

To my beloved family, especially my parents, my wife, my daughters, and my sons.

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Samir Y. S. Alnahhal
Technische Universität Berlin
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Abstract

Sanitation is of special concern to the international community, particularly in emerging countries. Lack of sanitation is one of the world's leading causes of disease and child death. Worldwide, current progress on sanitation is not sufficient to meet the target of Millennium Development Goals and the sanitation crisis is expanding. Currently, conventional sanitation approaches, both water-based and dry-based, are not designed for effective recovery of valuable resources. Consequently, the economic and environmental sustainability of these approaches may still be questionable. Therefore, sanitation management requires an urgent paradigm shift based on the concept of sustainable sanitation. One of the possible approaches to cope with the sanitation crisis is a resource-oriented approach that considers not only protection of human health and the environment but also closes loops on water and nutrients.

Through this thesis, a resource oriented sustainable sanitation (ROSS) module was designed and developed to reuse resources and recover nutrients from wastewater at a household level. The two main wastewater streams, mainly blackwater and greywater, are collected separately. The blackwater passes through a solid-liquid separator, where blackwater solids are separated and stored in a filter bag until a suitable time for further treatment. The blackwater liquid collected from the separator flows through a tank for nutrient adsorption by charcoal before entering a subsurface flow wetland for further purification. The treated effluent can be collected and stored in a storage tank before reuse in irrigation. Excess effluent from the storage tank flows to another tank for groundwater recharge. The blackwater solids and charcoal can be treated via lactic acid fermentation and composting for producing a Terra Preta-like substrate. Similarly, solids organic wastes may also be treated and added to the Terra Preta-like substrate before reuse in aquiculture.

Based on the concept of a ROSS module, two decentralized prototypes were implemented and realized in two households in the Gaza strip, depending on locally available resources and materials. The workability and efficiency of the module was investigated by monitoring one prototype. The module products, including the treated effluent and Terra Preta-like substrate, were inspected through testing composite samples collected in two rounds for the effluent and one round for the substrate. The finding of the sampled effluent revealed that the module was capable to removed 94.1% of total suspended solids, 78.9% and 86.1% of biological and chemical oxygen demand, respectively, and 99.4% of faecal coliform. The sampled substrate demonstrates acceptable properties as compared to the good compost produced from faceal materials. The total nutrient content and organic matter of sampled substrate were 2.373%, and 74.93%, respectively. The lead and cadmium concentrations were below maximum restricted limits and no faecal coliform was measured in the sample. However, the parasitic worm "Ascaris Ova" was noticed in the sample. The presence of this worm may limit the use of the substrate in planting vegetables. Moreover, following good hygiene practices, e.g., hand washing and wearing hand gloves, are highly recommended when using such products.

Kurzfassung

Das Sanitärwesen ist für die Weltgemeinschaft von besonderer Bedeutung, insbesondere in Schwellenländern. Der Mangel an Sanitäranlagen ist eine der Hauptursachen für Krankheiten sowie die Kindersterblichkeit. Die bisherigen, weltweit erreichten Fortschritte sind nicht ausreichend, um die Millenniumziele der United Nations zu erreichen. Tatsächlich weitet sich die Krise im Sanitärwesen sogar noch weiter aus. Konventionelle Wasser- und Trockentoiletten wurden ohne die Rückgewinnung wertvoller Ressourcen entwickelt. Folglich ist die ökonomische und ökologische Nachhaltigkeit dieser Ansätze fraglich. Das Sanitärwesen erfordert einen dringenden Paradigmenwechsel auf Grundlage des Konzepts nachhaltiger Sanitäranlagen. Eine vielversprechende Vorgehensweise zur Bewältigung dieser Krise im Sanitärwesen ist ein ressourcenorientierter Ansatz, der nicht nur dem Schutz der Gesundheit des Menschen und der Umwelt dient, sondern auch der Schließung des Wasser- und Nährstoffkreislaufes.

In der Arbeit wurde ein ressourcenorientiertes nachhaltiges Sanitäranlagenmodul (ROSS, englisch: resource oriented sustainable sanitation (ROSS) module) entwickelt, dass der Wiederverwendung und Rückgewinnung von Nährstoffen aus dem Abwasser von Haushalten dient. Die beiden wesentlichen Abwasserströme, Schwarz- und Grauwasser, werden separat gespeichert. Das Schwarzwasser wird anschließend durch einen Separator geleitet, um Feststoffe vom Schwarzwasser zu trennen und in Sackfiltern für eine gewisse Zeit zur weiteren Verarbeitung zu speichern. Das Schwarzwasser, das von Feststoffen getrennt wurde, fließt nun durch einen Tank zur Nährstoffadsorption, der Holzkohle enthält, bevor es in ein unterirdisches Feuchtbiotop zur weiteren Klärung fließt. In einem Tank wird das behandelte Abwasser gelagert, bis es zur Bewässerung wiederverwendet werden kann. Das behandelte Abwasser fließt vom Speichertank zu einem unterirdischen Grundwasserneubildungstank. Die Feststoffe aus dem Schwarzwasser und die Holzkohle können durch Milchsäuregärung und Kompostierung für die Herstellung von Terra Preta ähnlichem Substrat behandelt werden. Ähnlich können organische Feststoffe behandelt und zu dem Terra Preta ähnlichen Substrat hinzugefügt werden, bevor sie in der Landwirtschaft wiederverwendet werden können.

Basierend auf dem Konzept des ROSS module wurden zwei dezentrale Prototypen implementiert und in zwei Haushalten im Gazastreifen in Abhängigkeit von lokal verfügbaren Ressourcen und Materialien realisiert. Um die Machbarkeit und Effizienz des Moduls zu untersuchen, wurde ein Prototyp anhand einiger Qualitätsparameter in zwei Runden für das behandelte Abwasser und in einer Runde für das Terra-Preta ähnliche Substrat geprüft. Das Ergebnis des untersuchten behandelten Abwassers ergab eine Trennung von 94,1 Prozent der Schwebstoffe, von 78,9 Prozent bzw. 86,1 Prozent des biologischen und chemischen Sauerstoffbedarfs bzw. 99,4 Prozent der Fäkalcoliforme. Das Substrat zeigt im Vergleich zu Kompost aus Fäkalien akzeptable Merkmale auf. Der Nährstoffgehalt und organische Substanz der untersuchten Substrate liegt bei 2,373 Prozent bzw. 74,93 Prozent. Die Blei- und Cadmiumanteile waren unterhalb der Höchstgrenze und keine Fäkalcoliforme waren nachweisbar. Es wurde jedoch festgestellt, dass parasitäre Würmer wie Ascaris Ova die Nutzung für das Anpflanzen von Gemüse limitieren können. Ferner sollten hygienische Vorsichtsmaßnahmen, wie Händewaschen und das Tragen von Handschuhen, bei der Nutzung solcher Produkte berücksichtigt werden.

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List of abbreviations

%	Per cent
μS/cm	MicroSiemens per centimetres
BOD	Biological oxygen demand
BOD_5	Biological oxygen demand at 5 days
Cd	Cadmium
Cfu	Colony-forming unit
Cl	Chloride
cm	Centimetre
C:N	Carbon to nitrogen ratio
CO_2	Carbon dioxide
COD	Chemical oxygen demand
CW	Constructed wetland
d	Day
DO	Dissolved oxygen
dS/m	Deci-Siemen/meter in SI Units (equivalent to 1 mmho/cm)
EDCs	Endocrine disrupting chemicals
EM	Effective microorganisms
Eq.	Equation
FAO	Food and Agriculture Organization
FC	Faecal coliform
FWS	Free water surface
g	Gram
HDPE	High Density Polyethylene
HF	Horizontal flow
HRT	Hydraulic retention time
HSSF	Horizontal subsurface flow wetlands
ICP	Inductively Coupled Plasma
i.e.	In other words.
“	Inch
km^2	Square kilometre

l/p.d	Litres per person per day
l/p.y	Litres per person per year
LAF	Lactic acid fermentation
LDPE	Low density polyethylene
LDPE	Low density polyethylene
m	Metre
m/day	Meter/day
m^3/day	Cubic meter per day
MC	Moisture content
MDGs	Millennium Development Goals
MEH	Mohammad El Hessi
meq/l	Milli-equivalents per litter = mg/l ÷ equivalent weight of constituent ion
mg/l	Milligrams per litter, equals parts per million (ppm)
MJ	Megajoule
mm	Millimetre
mmho/cm	Millimhos per centimetre
MPN	Most probable number
N	Nitrogen
NaCl	Sodium chloride
NH_3	Ammonia
NH_4^-	Ammonium ion
nm	Nanometre
NO_3	Nitrate
OM	Organic matter
P	Phosphorous
Pb	Lead
PCPs	Personal care products
P.E.	Polyethylene
p.e.	Person equivalent
PCBS	Palestinian Centre Bureau of Statistics
pH	Acidity or basicity
PO_4	Phosphate

PPE	Polypropylene
PVC	Polyvinyl Chloride
PWA	Palestinian Water Authority
R&D	Research and development
REH	Ramadan El Hessi
ROSA	Resource-oriented sanitation approach
ROSS	resource-oriented sustainable sanitation
SLS	Solid-liquid separator
SP	Sampling point
SS	Imhoff (settleable solids)
SSF	Subsurface flow wetlands
TDS	Total dissolved solids
TKN	Total kjeldahl nitrogen
TOC	Total organic carbon
TOM	Total organic matter
TP	Terra Preta
TPS	Terra Preta sanitation
TS	Total solids
TSS	Total dissolved solids
TUHH	Technische Universität Hamburg
UASB	Upflow anaerobic sludge blanket digestion
UDDT	Urine diversion dry toilet
UN	United Nation
VC	Vermicomposting
VF	Vertical flow
VIP	Ventilated improved pit latrines
VSSF	Vertical subsurface flow wetlands
WHO	World Health Organization
WWTP	Centralized wastewater treatment plant

List of formula symbols

I	Inflow (m3/day) duration time, Δt
O	Outflow (m3/day) duration time, Δt
W	Change in water volume (m^3)
Δt	Duration time
Q_Δ	The total amount of flow that the wetland needs to disperse during major storm event (m^3/day)
Q_w	Average daily flow of greywater and liquid wastewater (m^3/day)
Q_p	Average daily rate of precipitation (m^3/day)
Q_e	Average daily rate of evaporation (m^3/day)
Q_{wu}	Average plant transpiration and water uptake (m^3/day)
C_e	Effluent BOD_5 (*mg/l*)
C_o	Influent BOD_5 (*mg/l*)
K_T	Temperature dependent rate constant (d^{-1})
T	Temperature of liquid in the bed (°*C*)
t	hydraulic retention time (*d*)
θ	Temperature coefficient for rate constant, equals 1.06
K_{20}	Temperature coefficient for rate constant, equals 1.104 (d^{-1})
L	Length of bed (*m*)
W	Width of bed (*m*)
n	Effective porosity of media (*%*)
d	Average depth of liquid in bed (*m*)
A_s	Bed surface area (m^2)
q	Flow per unit time, (m^3/d)
k_s	Hydraulic conductivity of a unit area of the media perpendicular to the flow direction ($m^3/m^2/d$)
A	Cross-sectional area, perpendicular to the flow direction (m^2)
I	Hydraulic gradient of the surface water flowing in a bed $\Delta h/L$ (*m/m*)
Δh	Head difference (*m*)
V_{TS}	Total volume of blackwater solids

Glossary

Term	Definition
Activated sludge	A secondary process for treating wastewaters by blowing air or oxygen for breaking down the organic material and settling them to form the faecal sludge. It often consists of aeration basin and secondary clarifier
Ascaris Eggs	A parasitic worms and a type of helminth that cause diseases and affect human. Their eggs are mostly found in faeces and soil
Biochemical oxygen demand (BOD)	The amount of dissolved oxygen that is required by aerobic organisms to biochemically break down organic material present in a certain water sample at a specific temperature over a particular time period. It is often used as an indicator for the degree of organic pollution of water or wastewater
Biodegradation	Biological conversion of organic material into basic compounds and elements, e.g., carbon dioxide and water, by bacteria, fungi, and other microorganisms.
Bit latrine	Consists of a seat or squatting hole made over a pit that collects the human excrement and should be desludged when become full.
Blackwater	Black water refers to the wastewater stream that comes from toilets, containing urine, faeces, anal cleansing materials, anal cleansing water, and flushing water
Charcoal	A lightweight, porous black solid, and consisting of carbon and any remaining ash. It is a residue obtained by removing water and other volatile constituents when wood, bone, or other organic matter is heated in the absence of oxygen
Composting	Composting is a controlled aerobic degradation process for decomposing of an organic matter contained in biodegradable wastes, e.g. agricultural and food wastes, and wastewater, with the help of microorganisms, mainly bacteria and fungi to produce an a soil conditioner or odourless organic fertilizer
Constructed wetlands (CWs)	Typical engineered treatment equipment that are mainly designed and operated as a biological sand filtration bed. The treatment of variety of liquid wastes, including domestic wastewater depends on natural principles by involving wetland vegetation, filtration media, and associated microorganisms' colonies.
Disinfection	The process of removal, deactivation or killing pathogenic organisms by addition of chemicals, radiation, heating, or physical separation processes, e.g., membranes.

Ecology	The interdisciplinary field that includes biology, geography, and Earth science, and deals with the scientific analysis and study of interactions among organisms and their environment.
Effluent	Effluent refers to the treated or untreated liquid of wastewater that flows out of a process or certain place, or leaves a technology
Emergent aquatic macrophytes	Plants that are rooted in shallow water with vegetative parts emerging above the water surface
Escherichia coli	A gram-negative bacteria that originate in the digestive tracts of humans and animals. They cause diseases to humans and can cause food poisoning. they can survive outside the body for a limited time, this makes them potential pathogen indicator organisms for faecal contamination in water and wastewater in tested samples of water, wastewater, and compost substrate
Escherichia coli (E. coli)	A bacterium found in the gut, used as an indicator of faecal contamination of water.
Eutrophication phenomenon	Eutrophication phenomenon is the depletion of oxygen in a body of water, which kills aquatic infants due to the addition of excess nutrients, mainly phosphates. These nutrients make explosive growth of plants and algae, which consumes oxygen from the water [Scd-08].
Evapotranspiration	The sum of evaporation and plant transpiration. Evaporation is the movement of water to the air from soil and waterbodies.
faecal coliforms	A gram-negative bacteria that originate in the digestive tracts of humans and animals. It is commonly used as an indicator of faecal contamination in tested samples of water, wastewater, and compost.
Faecal sludge	A mixture of biosolids wastes and water, containing also sand, grit, trash, metals and various chemical products used in the household. It settles to the bottom of latrines, septic tanks and ponds or is produced from the treatment of wastewater in the wastewater treatment plant
Faeces	Faeces refers to a solid or semisolid metabolic waste from an animals or humans after food has been digested and discharged by a defecation process. It is not mixed with water or urine. Based on diet, an adult person produces 50L faces annually.
Fermentable carbohydrates	Composed of short chains of sugar molecules, making them easy to break down. Once these sugars reach the large intestine, bacteria rapidly ferment them
Gram-negative bacteria	A group of bacteria that are spread worldwide, in all environments that support life. The gram-negative bacteria include many pathogenic bacteria, e.g. Escherichia coli, faecal coliforms, and salmonella.

Greywater	Greywater refers to the wastewater stream comes from the kitchen, bath and/or laundry. It generally does not contain significant concentrations of pathogens and nutrients "
Helminth egg	Parasitic worm organisms living in and feeding on living hosts, which when become matured can be seen with necked eyes. The eggs have a strong shell against a range of environment conditions and able to survive for several years in their host. Ascaris is the name of a certain helminth.
Human excrement	Excrement consists of faeces and urine only, which is not mixed with any Flushwater. Although excrement has a small volume, it contains high amount of nutrients and pathogens
Hydraulic retention time	A time needed to allow wastewater to pass and flow through a system or treatment equipment
Improved sanitation	Includes sanitation facilities that likely ensure hygienic separation of human excrement from human contact, including flushing toilets, piped sewers, septic tank, pit latrine, ventilated improved pit latrines, pit latrine with slab, and composting toilet
Indicator organisms	Microorganisms that presence give indication of faecal contamination in the wastewater and possibly indicative to the presence of more harmful microorganisms
Log reduction	Stands for a 10-fold or one decimal. A 1 log unit reduction in number of living bacteria means that 90% of number of bacteria is reduced. 2 log units means 99% removal of microorganisms; 3 log units = 99.9%; and so on
Mineralization	A biological process in which organic materials are converted to inorganic substances by soil microorganisms.
Nitrification	A two stage process for the biological oxidation of ammonia or ammonium to nitrite followed by the oxidation of the nitrite to nitrate in soil and water by means of microorganisms.
Nutrient recovery	The process of recovering nutrients, e.g., nitrogen and phosphorus from wastewater and converting them into an environmental friendly fertilizer used in agricultural activities. This process helps clean the wastewater effluent by removing these nutrients from the effluent before discharging into the environment
Nutrient removal	The process of removing nutrients e.g., nitrogen and phosphorus, from wastewater before reuse or discharge into the environment either biologically or chemically
Pathogens	Pathogens are the disease causing organisms, e.g. viruses, bacteria, fungi, protozoa and parasitic worms.

Permeability	A measure of the ability of a material, e.g., soils and rocks to transmit fluids through its pores. www.wikipedia.com
Porosity	Equals void volume to total volume of the bed, and is expressed as a percent. The porosity is used to determine the flow velocity in the void spaces, it is also used to determine the size of the vegetation bed of the SSF wetland
Pre-treatment	See Primary treatment
Primary treatment	Initial treatment process of wastewater used to remove bulk inorganic solids settleable organic and by sedimentation and floating substances by skimming. Examples of primary treatment equipment include septic tanks, Imhoff tanks and solid-liquid separation tanks
salmonella	A gram-negative bacteria that can survive with or without oxygen and are not destroyed by freezing but Ultra Violet light disinfection and heat prohibit their growth and accelerate their destruction. It can be found in the digestive tracts of humans and animals
Sanitation	Sanitation is the hygienic means of protecting health through prevention of human contact with the wastes, it includes solid and medical waste disposal, wastewater disposal, wastewater reuse, human excrement disposal, and drainage of runoff or rain water.
Sanitation ladder	A helpful tool is being used to monitor progress towards the sanitation target of the Millennium Development Goals (MDGs)
Scum	A layer of unpleasant or unwanted material, e.g., dirt or froth that has formulated on the surface of a liquid.
Secondary treatment	Wastewater treatment step that follows primary treatment and is the treatment process for wastewater to achieve a certain degree of quality to the effluent. The treatment involves the removal of biodegradable organic material either naturally or chemically. Examples of secondary treatment include constructed wetlands, trickling filters, oxidation ditches, and aerated lagoons.
Septic tank	A tank is built underground to collect and treat wastewater by means of settlement of solids and anaerobic digestion. The effluent liquid may be discharged into another treatment equipment e.g. constructed wetlands or soak pits, or into a water-borne sewers
Sewage	A mixture of human excrement and flushwater that flows through the pipes; it also includes wastewater produced from other streams, e.g., greywater or rain water.
Sewer	A pipe or conduit that carries wastewater or drainage water from production location to other location for treatment, reuse, or final disposal

Sewerage	A complete network of pipes, electrical pumps, basins, tanks, unit processes and infrastructure for the collection and transport of wastewater to the location of treatment or final disposal
Silage	A grass or other green fermented fodder produced by compaction and storage in airtight containers before being dried. It can be used to feed livestock or used as a biofuel feedstock for anaerobic digesters.
Stabilization	See biodegradability
Terra Preta soil	A very dark, nutrient-rich soil that is found in the Amazon Basin due to the man-made activities of pre-Colombian people
Tertiary treatment	The treatment steps added after the secondary treatment stage and is the final cleaning process to improve the wastewater quality before reuse or safe disposal into bodies of water. The treatment is often used to remove specific constituents and inorganic compounds, e.g. phosphorus and nitrogen.
Unimproved sanitation	Includes sanitation facilities that do not ensure hygienic separation of human contact from human excrement. Unimproved facilities include pit latrines without a slab or platform, bucket latrines, and hanging latrines.
Urine	Urine is the liquid produced from the metabolism in the bodies of animals and humans. Approximately, an adult person produces 300-550 L of urine annually
Waste stabilization ponds	Shallow basins that treat wastewater or faecal sludge depending on natural conditions e.g. sunlight, temperature, sedimentation, and biodegradation, and with the help of microorganisms and algae. The ponds usually consist of anaerobic, facultative and maturation ponds and can be used individually or linked in series for improvement of wastewater treatment.
Wastewater	A Liquid waste discharged from homes, commercial or business buildings, which contains mainly human excrement, flushing water, and other used water in the kitchen, laundry, shower. When it is produced by household, it is called domestic wastewater. Domestic wastewater also does not contain liquids from industrial activities at levels. Discharging wastewater without treatment could pose threats to public health and the environment
Wetland	A place where the land is saturated with water either seasonally or permanently and characterized by vegetation of aquatic plants e.g., common reed plant. Some examples of wetlands are marshes and ponds, an edge of a lake or ocean, and delta of a river.

1. Introduction

1.1. Motivation

Water and sanitation are fundamental to well-being and human development. They are crucial to achieving other development goals, including eradication of poverty, and attaining an education, gender equality, and adequate nutrition. Obtaining access to safe water and sanitation is a human right, as recognized by the United Nations General Assembly in 2010 [WHO-15].

Globally, sanitation is recognized as a cornerstone of human health, environment, and human dignity. It is also well recognized that human mortality is closely associated with poor sanitation, unsafe drinking water, and inadequate hygiene, which contribute to the death of a child every 20 seconds [Crc-10].

The clearly manifesting crisis in sanitation is a special concern of the international community and the United Nations (UN). In view of the rising sanitation crisis worldwide, the UN Member States signed the Millennium Declaration in 2000, which later led to formulation of the Millennium Development Goals (MDGs). Under goal 7 that focuses on ensuring environmental sustainability, "target 10" was to halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation. With respect to MDG targets, global coverage of the access to improved sanitation rose from 54% in 1990 to 77% in 2015. The MDG target for global coverage of the use of improved drinking water sources, which was intended to rise from 76% in 1990 to 88%, was globally achieved in 2010. Over 90% of the global population used an improved source of drinking water in 2015. However, the target for sanitation has not been met and has been missed by almost 700 million people. Only 68% of the global population have accessed improved sanitation facilities, 82% in urban areas and 51% in rural areas, leaving 2.4 billion—more than one-third—of global population without access to improved sanitation facilities [WHO-15], as shown in Figure 1-1.

Worldwide, current progress on sanitation is not sufficient to meet the MDG target [WHO-14]. Therefore, the world must address not only the coverage need for sanitation, but also the problem of open defecation, which still is practiced by almost a billion people (approximately 946 million). Open defecation, an indicator for extreme poverty, should be eliminated by 2025 according to the UN call to action on sanitation in 2013 [WHO-15].

The crisis in sanitation is expanding because of the rapid growth of population, enhancement of living standards, and global urbanization. Actions to meet the MDG sanitation target are urgently required. Any sanitation approach should be designed, developed, implemented, and practiced based on the concept of sustainable sanitation, which should not only protect human health and the environment but also should be economically viable and socially accepted. It also should recognise the human excrement and wastewater not as wastes but as valuable resources, and should incorporate all parts of the sanitation service chain that includes containment, collection, transfer, treatment, and reuse, and disposal [SuSanA-08]. One of the possible approaches to cope with this sanitation crisis is a resource-oriented approach that considers not only protection of human health and the environment, but also closes the loops on water and nutrients.

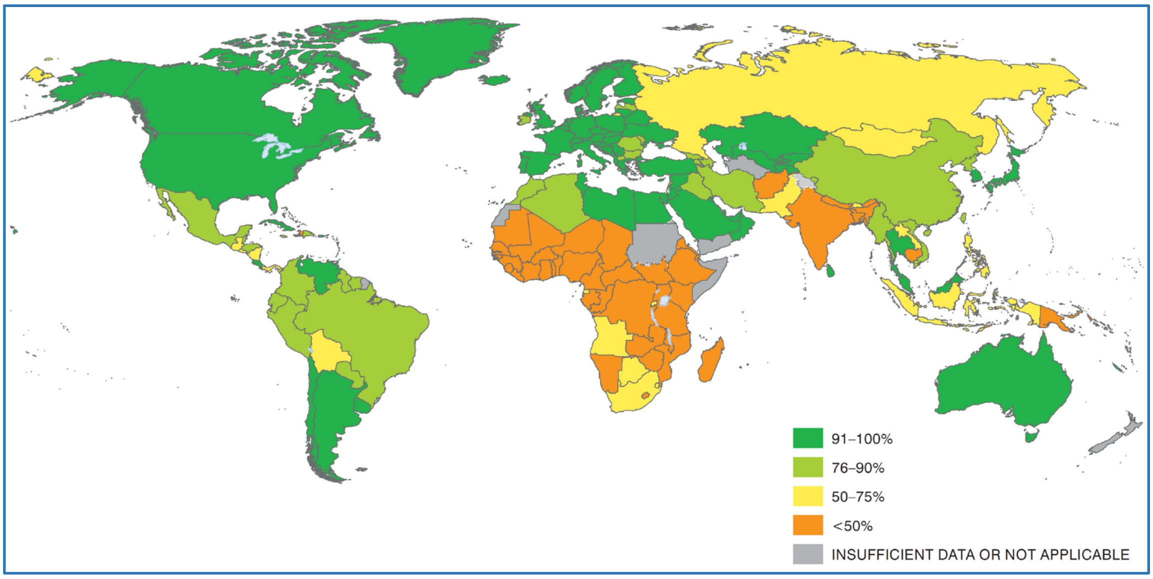


Figure 1-1: Countries, areas, or territories access to improved sanitation in 2015. Reprinted from: [WHO-15]

1.2. Objectives

The main focus of this research study is to design, develop, realize, and monitor a sanitation prototype in the Gaza Strip based on the concept of resource-oriented sanitation. This prototype will aim to handle and manage domestic wastewater and solid organic wastes, e.g., food residuals, on-site in a safe and hygienic manner. The prototype shall be low-cost; low-tech; and easy to implement, operate, and maintain; as well as culturally adoptable for communities in semi urban and rural areas in emerging countries. This decentralized approach consists of Terra

Preta sanitation (TPS) and constructed wetlands (CWs). TPS converts bio-solid wastes, including solids of blackwater and solid organic wastes, into a soil conditioner or Terra Preta-like substrate in a hygienic and sustainable manner [Fac-10]. In addition, CWs treat liquid wastewater (i.e., greywater and liquid of blackwater) and offer a treated water for irrigation purposes in a safe and hygienic way [Hof-10].

Another challenging problem that has been addressed as an objective in this thesis is to design and develop solid-liquid separation equipment that can offer a good separation of blackwater solids from mixed wastewater in a manner that is safe, hygienic, and socially accepted. This equipment must be accomplished with consideration of the locally available resources and materials, and with no requirements for energy, e.g., electricity.

1.3. Structure of thesis

The structure of the thesis consists of seven chapters as shown in Figure 1-2. Chapter 1 consists of three sections. Briefly, the first section discusses the motivation of this research study, presenting the current coverage use of improved sanitation facilities, and the ways in which the international community has reacted to the sanitation crisis. The second section discusses the objectives of this thesis, while the last section outlines the structure of the thesis.

Chapter 2 discusses the conventional sanitation approaches in emerging countries in two sections. Briefly, the first section presents the architectures of the sanitation approaches regarding disposal of human excrement and wastewater by using either water or no water; methods of managing these wastes either on-site, off-site, or a hybrid of on-site and off-site; and eventually the release of such wastes into the environment, mainly via centralized and decentralized approaches. Also addressed are the conventional approaches, typically “flush and discharge” and “drop and store,” in light of sustainability dimensions, i.e., social, economic, and environmental aspects.

Chapter 3 focusses on the sustainable sanitation approach, and its concept and objectives. It also discusses the concept of the resource-oriented sanitation approach and handling and management of wastewater, human excrement, and solid organic waste, e.g., food residuals, using the decentralized sanitation approach. The main technological components used in this approach, e.g., a pre-treatment process and equipment, and constructed wetlands concepts are also discussed. The approach of Terra Preta sanitation that is used to manage bio-solid wastes is also discussed.

In chapter 4, this thesis tackles the research gap. The requirements of a resource-oriented approach for sanitation at the household level are analysed. Although current conventional sanitation approaches are generally widespread and can offer an acceptable level for human health, their sustainability is still questionable and their contribution to provide a clean environment is modest because they work in a linear manner with no opportunities to close loops for water and nutrients.

In chapter 5, the concept of resource oriented sustainable sanitation module is presented. A sanitation service chain on the basis of the resource-oriented sustainable sanitation module is developed for an on-site prototype that handles and manages liquid and bio-solid wastes at a household level. The technological components for the sustainable sanitation modules are discussed. In the decentralized module for managing liquid wastes, including greywater and liquid blackwater, the concept and the key functions of pre-treatment solid-liquid separation equipment and constructed wetland equipment are presented. Furthermore, basic concept and requirements for Terra Preta sanitation, primarily lactic acid fermentation and composting, are presented for managing the bio-solid wastes, including blackwater solids and food residuals, as well as the integration to water–based sanitation approaches is also presented.

Chapter 6 presents the realization of two decentralized prototypes in the Gaza Strip with focus on the design requirements and construction details including the specifications of materials and components required for the module implementation. In addition, the monitoring protocol, which includes the location of sampling points and some physical, chemical, and biological indicators for checking the workability and effectiveness of the module, is addressed. The laboratory results for sample testing indicators from one out of the two prototypes are presented and discussed.

Chapter 7 gives a summary, outlook, and future recommendations on the basis of the prototype implementation and monitoring results.

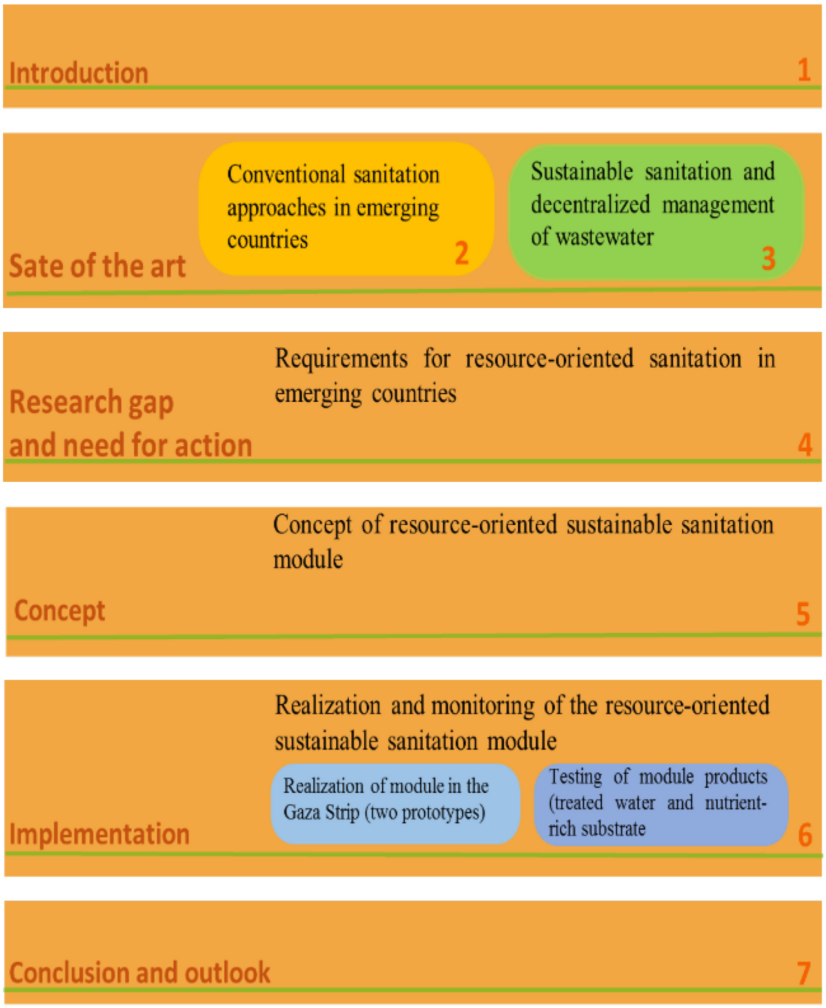


Figure 1-2: Structure of the thesis

2. Conventional sanitation approaches in emerging countries

Since many centuries ago, when sanitation approaches were first invented, human excrements have been regarded as waste, and the working principal is to dispose of human excrements and different kinds of wastewater in a location either far away or near to their production. Globally conventional approaches are most dominant, mainly “flush and discharge” and “drop and store”. Although some of these approaches have made revolutionary changes in sanitation in terms of protecting human health and environment, and other approaches are more affordable and used more heavily in emerging countries with less assurance of human health and environment protection, the long-term sustainability of such approaches remains questionable [Wer-09, p. 392].

In the following sections, the author will discuss different conventional sanitation architectures and review their sustainability, focusing on social, economic, and environmental aspects.

2.1. Architectures

In literatures, architectures of sanitation approaches can be distinguished based on different aspects:

- For disposal of human excrement with or without water, “wet” and “dry” approaches are widely used.
- For different ways of handling human excrement, “on-site”, “off-site”, and “hybrid” approaches are used.
- Release of human excrement to the environment is accomplished via “decentralized” and “centralized” approaches.
- For human health concerns, “unimproved” and “improved” approaches are well known in the “sanitation ladder” that is commonly used by the World Health Organization (WHO).

It is notable that some sanitation approaches may fall somewhere between these categories. Examples are the treatment of faecal materials, e.g., blackwater solids and faecal sludge, on-site but the transportation of liquid wastes from on-site to off-site for further treatment or disposal; or when water is added in small quantities to the dry approaches[CSIR-00]. Furthermore, another differentiation can be made based upon the separation from source for different kinds of wastewater, e.g., blackwater or greywater [Lüt-09, p. 458]. More information and technical description on the different sanitation categories and examples of each categories are provided by [Par-08],[CSIR-00], [Til-08],[Til-14].

In line with the scope of this thesis, the author focuses on the handling methods and effluent release of human excrement to the environment, e.g., bodies of water, surface land, or atmosphere, and the terms “centralized” and “decentralized” will be used for distinguishing between these approaches. The decentralized approach releases the wastewater effluent to surface land or into soil, while the centralized approach releases the effluent into bodies of water, e.g., rivers, lakes, seas, and oceans [Jan-06, p. 32].

2.2.1. Decentralized approach

The decentralized sanitation approach serves a small community or a certain area [USEPA-05]. It is generally referred to in terms of wastewater handling methods, including treatment, disposal, or reuse in the vicinity of wastewater production [Cri-98], [Jan-06, p. 32]. It commonly consists of several treatment plants, but not one central plant. These plants are not typically smaller in size and or not confined to a subset of served people [Lib-12, p. 62]. Fundamentally, the decentralized approach has several aliases, including “on-plot” [Cot-98], “on-site system”, “individual wastewater system”, “on-lot system”, “cluster system”, community system” [Jan-06], and “simplified sanitation system” [Ort-07]. It can also be subdivided into two main approaches, namely “on-site” and “cluster” approaches [USEPA-97, p. 2], [USEPA-04, p. 21]. The on-site approach is common in rural areas and for poor communities in semi-urban areas [Pat-07].

On-site approach

The on-site approach serves a single house, business, or facility [USEPA-04]. Principally, human excrement is accumulated and stored in a pit, septic tank, or vault near the toilet [Srl-02], [Par-08], which requires emptying or desludging when it becomes full [UN-Water-15]. The on-site approach can be further distinguished based on the usage of water for discharging the human excrement from the toilet as “dry on-site” or “wet on-site” [Par-08].

The dry on-site approach, when water is not used as a carrier to dispose of the human excrement, is also known as “dry sanitation” [Psy-00],[Eli-02], or “drop and store” [Win-97], [Esr-01],[Wer-03]. A pit latrine is the best example of this type [Esr-01]. This approach also includes not only a wide range of low-cost on-site models, e.g., pit latrines, ventilated improved pit (VIP) latrines [Psy-00], double vault composting latrines, and pour-flush toilets [Pat-07], but also modern designs that are promoted to handle the human excrement safely [Par-08]. The conventional treatment processes for dry on-site approach are either dehydration or composting [Ort-07]. Both processes depend on nature for assimilating human excrements [USEPA-97]. In the dehydration process, urine is separated from faeces and diverted to a container for storage, while the faeces is kept to dehydrate faster with less water content [Psy-00], [Brk-03]. In contrast, composting treatment is a biological process for producing a soil conditioner or compost from faeces by controlling local conditions, e.g., temperature, moisture, and airflow[Brk-03], [Psy-00]. Until now, several types of dry on-site approach are practiced in many places over the world, including China, central America, Sweden [Srl-02], and the Philippine [Itc-13].

The wet on-site approach uses water for discharging human excrements, in which all kinds of wastewater are combined together. However, for higher water quantities of more than 30 litres per person per day (*l/p.d*), the separation between these types of wastewater is preferable. Generally, wastewater is released into soil via percolation pits or tanks [Par-08]. The traditional equipment of collection and on-site treatment is septic tank with soil adsorption bed [USEPA-04]. In this approach, flush water toilets are dominantly used.

Cluster approach

The cluster approach serves from two to several hundred buildings, e.g., houses, businesses, and facilities, in a small community [USEPA-05] rather than a town or city [USEPA-02]. It is also under some form of common ownership [USEPA-05], where alternative pipeline networks are used to collect and transfer wastewater for treatment and final disposal. Although the cluster approach falls in the decentralized category when a small decentralized treatment facility is used for wastewater treatment [USEPA-04], it sometimes becomes centralized when wastewater is treated in centralized plants [Jon-01]. Substantially, the cluster approach differs from the on-site approach in wastewater collections, flow patterns, and organic loads[USEPA-02].

For small communities in most emerging countries, the cluster approach is basically deemed as an environmentally sound and financially reasonable sanitation alternative [Jon-01], [Eng-06], where the on-site approach is not feasible due to site or soil difficulties and where centralized approaches have affordability drawbacks [Jon-01]. The cluster approach can used to bridge the gap between the on-site and off-site approaches, specifically where the use of these two approaches is not feasible. The cluster approach has other advantages in connection to high flexibility in land use and in planning for the future growth with less maintenance [Eng-06]. The cluster approach can also be subdivided into two categories based on treatment and disposal options: community-managed [Mar-10], and simplified sewerage [Bak-94], [Chn-12]. The community-managed approach has many aliases, including community-based sanitation [Pel-10], community system [Jan-06], communal sanitation [Sch-10], and shared sanitation [Hei-14], [WHO-15], while the simplified sewerage is also known as condominial sewerage [Lüt-11].

2.2.2. Centralized approach

At the turn of the last century, the centralized approach was termed the modern approach; today it is considered as the conventional approach [Sct-05]. It is also called flush and discharge [Win-97, p. 3] and end of the pipe [Ott-02]. It serves wide communities or big cities [Jan-06]. Principally, it was designed and developed to collect and transport wastewater from its production place, e.g., the toilet [Par-08], to elsewhere by using water as the transporting medium [Bha-01] through pipeline networks or water-borne sewers [UN-Water-15], in which all kinds of wastewater, and sometimes storm water, are mixed together [Lüt-09]. The centralized approach treats wastewater in a centralized wastewater treatment plant (WWTP) that typically is far away from the place of wastewater production.

Based upon wastewater collection and transport, two main types of centralized approach can be distinguished: combined sewers and separate sewers. In the combined sewers, wastewater and storm water are collected and transported in the same pipe, while in separate sewers, wastewater and storm water are collected and transported separately in two different pipes. Separate sewers are more preferable, as they are more effective and need less investment compared to combined sewers [UN-Water-15]. The separate sewers can be further classified as simplified sewer or conventional sewer [Chn-12].

2.2. Valuation

The conventional sanitation approach, typically either the flush and discharge or drop and store approach, considers human excrement as a waste that should be disposed of in the environment based on the following incorrect assumptions [Win-97, p. 3 f.]:

- The environment has a strong capability to safely assimilate all pollutants in wastewater.
- Freshwater resources are unlimited.

- Wastewater can be treated at end of the pipe.
- Disposal of wastewater is a fundamental problem.

Unfortunately, many years of research has proven that these assumption were wrong and the environment cannot assimilate all components of this waste in a short amount of time, especially with the rapid population growth and urbanization. Hence, such approaches were unable to make a significant impact to improve the sanitation for nearly half of the world's population, and even those approaches that have improved sanitation conditions remain questionable regarding long-term sustainability and ability to address the MDGs [Wer-09].

In line with the context of this research, evaluation of the conventional approach can be made based upon sustainability aspects: social, economic, and environmental.

2.2.1. Social aspects

For social aspects, no consensus has been made on an accepted assessment approach, because the indicators that can be used to evaluate a service or intervention are numerous [Pad-16, p. 102]. Therefore, to avoid the wide range of indicators used in the evaluation process, the author focuses on the most important indicators, including human health and public acceptance.

Human health

The human health risks caused by human contact or direct reuse of untreated wastewater are well recognized [FAO-16], [WHO-16]. The health aspects primarily refer to microbiological contamination and other toxic materials, e.g., heavy metals and chlorine derivatives [Nha-04] that are present in the wastewater. The microbiological contamination is caused by various pathogenic organisms, e.g., bacteria, viruses, fungi, protozoa, and parasitic worms, that are harmful to both humans and animals [WHO-89], [Aus-01] through causing different water-borne diseases [Kri-71], e.g., diarrhea, bacterial diseases and parasitic infections. The toxic materials, called also micro-pollutants, include pharmaceutical residuals, personal care products (PCPs), and endocrine disrupting chemicals (EDCs). The presence of these micro-pollutants in wastewater is caused by widespread production and use of drugs and chemicals for various purposes in recent years. The micro-pollutants could cause severe human health concerns [Wil-16], even with very low concentrations [Muñ-09], [Jia-13] because they show high stability [Muñ-09], are not biodegraded easily [Jia-13], and can dissolve readily in water. Universally, more than 80 compounds of pharmaceutical residuals, PCPs, and EDCs have been observed in raw and treated wastewater and aquatic environments [Jia-13] as stated in recent investigations conducted in the U.S.A, Canada, Brazil, England, Germany, Spain, Italy, Switzerland, Greece, The Netherlands, Croatia, Austria [Heb-02], France, Finland, Belgium, China, and Japan [Jia-13]. Moreover, some micro-pollutants have seeped through the soil to end up in the groundwater, as observed in some samples in Germany [Heb-02, p. 14].

In the flush and discharge, called also FlushSan approach, protection of human health is the first priority [Mug-08], [Lüt-09]. The water-flush toilets are dominantly used at the household level and can offer an acceptable level of safety and hygiene [Til-14], [Kro-16]. Employing disinfected water in these toilets can significantly improve the level of pathogen destruction [Sct-05]. However, such toilets cannot completely guarantee elimination of potential health risks, e.g., disease transmission, if the health awareness level is low and the personal practices are hygienically poor [Aus-01], [WELL-98].

The water-borne sewers used for collection and transport the wastewater are deemed as a safe and hygienic means of protecting human health, if effectively managed [UN-Water-15], i.e., well-constructed and periodically maintained [Til-14]. However, the well-known benefits of water-borne sewers [Mug-08], [Lüt-09] do not make them the only solution available or even the most appropriate one [SuSanA-08]. Furthermore, any potential failure causes severe implications on human health, because wastewater overflows and flooding. Many cases of sewer failure have occurred worldwide, particularly in emerging countries [Brk-03]. In addition, any malfunction in electrical pumps that are used to lift wastewater in the water-borne sewers causes serious problems, including overflowing, pipe leakage, and malfunction in wastewater treatment facilities [UN-Water-15]. A similar case of failure in the electrical pumps happened in al-Zaytoun in eastern Gaza city, the Gaza Strip in November 2013. About 35,000 cubic meters of a mixture wastewater and rainwater [Gisha-13] raised the level of water to reach 110 cm inside residential houses [Jal-13]. Various areas in the Gaza Strip, where FlushSan is provided, have experienced several wastewater overflows due to lack of resources, e.g., fuel and electricity, which are required for proper operation, and inadequate design for heavy storm events.

Generally, the well-equipped WWTPs contain three treatment processes, named physical or mechanical treatment for screening and removing bulk materials, biological treatment for biodegrading the organic materials, and tertiary treatment for removing nutrients from the wastewater effluent. These three processes encompass the current state of the art of wastewater treatment [Sct-05], [Lüt-09]. In each process, there is a wide range of conventional unit processes, including pre-treatment and primary sedimentation, biological oxidative processes, post-sedimentation, trickling filters, and typical disinfection practices. These unit processes alone are not appropriate to ensure a high level of health protection, as they do not appear to be sufficient to completely destroy pathogens[Kri-71], [Fea-83]. Well-managed conventional WWTPs have significantly enhanced human health [Wer-03],[Lng-11]. However, the effluents from these plants still contain considerable amounts of pathogens. This makes these effluents inadequate for direct reuse in agriculture [Kri-71], [Fea-83]. Many recent studies have claimed the shortcomings and poor efficiencies of conventional wastewater treatment processes, e.g., activated sludge and bio-filtrations, for safe removal of micro-pollutants, as they simply are not designed for such specific tasks [Ott-01], [Ott-02], [Dor-10], [Jia-13]. This agrees with the results found in a field study of seasonal stabilities and removal efficiencies for 25 micro-pollutants in four full-scale conventional wastewater treatment plants for relatively small communities (<2000 population equivalent, *p.e.*) in Spain. The average removal efficiencies for horizontal subsurface flow wetland, extended aeration-new version of activated sludge, rotating biological contactor, and waste stabilization pond were 42%, 62%, 63%, and 82% respectively[Mat-16].

The current state of the art for WWTPs includes advancements and sophisticated treatment processes compared to the conventional plants for promoting the quality of wastewater effluent to the level that it can be reused safely for various purposes, including drinking water supplies if needed [Kri-71, p. 38]. The sophisticated treatment processes, including ozonation, membrane filtration, advanced oxidation, and activated carbon adsorption, are required to meet standards of effluent reuse or disposal, which may become more restricted in the future. However, there is no framework that can broadly identify the optimal set-up for such advanced processes to be integrated in the current service chain of the FlushSan approach [Wil-16, p. 151], which may include containment in flushing toilets, collection via household connections, transport via water borne sewers, central treatment via WWTP, and effluent reuse or safe disposal.

From another point of view, the drop and store approach can protect human health, effectively, if properly designed, developed, operated, and maintained [Esr-98, p. 7 f.], [Psy-00], [USEPA-04, p. 21], and when linked to good hygiene practices by the users [Eli-02, p. 23], [Bha-08, p. 25 f.], [Par-08, p. 34]. The most important health concern is the potential of such an approach to pollute groundwater with a high content of nitrates that severely affects human health and causes death of babies if it exceeds WHO standard limits [Wer-03, p. 4]. Therefore, lack of management and health promotion makes these approaches hygienically unsuitable solutions and human health protection is not guaranteed, as many cases in poor communities [Lüt-11, p. 24].

Public Acceptance

The FlushSan approach have been accepted by the vast majority of people since the turn of the last century. FlushSan approach is also deemed as the ideal option and the most practical to use in urban areas [Win-97, p. 3 f.], [Esr-98, p. 7 f.], [Sct-05, p. 7]. Moreover, many professionals and decision-makers consider this approach as the only appropriate solution to urban sanitation [Bha-01], [Sct-05].

The drop and store approach is also publically accepted as an alternative or temporary solution to the FlushSan approach for poor communities in rural areas in emerging countries [Esr-98, p. 7 f.], although the people in most urban areas always prefer to have access to the FlushSan approach [Par-03, p. 80], [Pat-07]. This is because of the drawbacks of the drop and store approach, including lack of enough space for digging pits, challenge of deep digging in available landscape or rocky soil, potential pollution of groundwater if water tables are high, challenge of destabilizing foundations of existent buildings, continuous occurrence of offensive odour, and provision of suitable breeding environments for flies and other insects, e.g., mosquitoes [Esr-98, p. 7 f.], as well as short life cycle, high collapse risk [Win-97, p. 5], [Bha-08, p. 25 f.], and potentials for overflow and flooding in rainy seasons [UN-Water-15, p. 16]. As a result, the conventional form of drop and store, the pit latrine, is built away from the house [Esr-01, p. 11] because people do not prioritize building of pit latrines inside their houses, particularly high standard houses [Dra-97, p. 11]. This makes their users, particularly women and children, feel uncomfortable and undignified [Wer-03, p. 4].

2.2.2. Economic aspects

Sanitation is a profitable investment, and the provision of improved sanitation has undeniable impacts on people's health and the economy [Min-11]. The economic aspect is a crucial issue in sanitation, particularly in emerging countries [Poy-13, p. 315] because

- Sanitation problems are growing in many urban areas in both industrialized and emerging countries with the growth and urbanization of the world's population.

- Available water resources are becoming scarce and highly polluted due to unrestricted discharge of wastewater to bodies of water, soil, and the atmosphere, resulting in extra costs in terms of human health and the environment.
- Current wastewater treatments are inefficient and ineffective in most emerging countries.

The author sheds light on affordability, construction, operation and maintenance costs, and reuse revenues as the most important indicators for evaluating the conventional sanitation approaches, primarily flush and discharge and drop and store, in terms of economic considerations.

Affordability

In the FlushSan approach, the affordability is an extreme challenge to decision makers, as provision of FlushSan requires huge resources, e.g., energy [Crm-13, p. 5484], water, finances, and institutional capacities [Lüt-11, p. 26 f.], and technical expertise for operation and maintenance [Flo-09, p. 2973]. The high financial costs make FlushSan economically infeasible for both rural communities [Mei-09, p. 1], [Poy-13, p. 314] and poor urban communities [Pat-07, p. 903], [Pri-08, p. 259]. These communities cannot alone cover the high costs of FlushSan [Gaj-03, p. 133], as observed in many cases in Mexico, India, Pakistan, and Cambodia [Rsm-05, p. 114].

The drop and store approach is affordable to most people in rural and semi-urban areas in emerging countries due to its relatively low cost [Ort-07, p. 260], [Par-08, p. 31].

Construction, operation, and maintenance costs

The FlushSan approach needs not only high investment for construction, but also for operation and maintenance [Lng-11, p. 65], [Lüt-11, p. 26 f.], as well as supporting the capital cost for an extended time [Sut-13, p. 1115], which is problematic for small communities of less than 2000 population equivalents, *p.e.* [Crm-13, p. 5484]. In FlushSan, collection and transport of wastewater via water-borne sewers and electrical pumps are the most expensive components in terms of the total capital cost [UN-Water-15, p. 15], which approaches 70 % to 90% of the overall investment [Bra-08, p. 216]. Collection and transport of wastewater should be designed to fulfil the needs for future years due to population growth. This makes the required capacity of sewers and pumps much greater than the current situation, and increases their anticipated costs [Wil-00, p. 4]. Moreover, construction of new collection systems and expansion of available services are not able to keep pace with the rapid population growth and urbanization, which require more costs and time [SuSanA-08, p. 4]. Other high financial costs are also associated with construction, operation, and maintenance of wastewater treatment and reuse, which require significant amounts of energy [Lng-11, p. 66], land space [WHO-89, p. 10], chemicals [Sct-05, p. 8], and materials [Thi-14, p. 45]. An estimation for annual costs of the FlushSan approach is provided by [Kro-16, p. 91].

The drop and store requires less costs compared to FlushSan in terms of construction, operation, and maintenance[Win-97, p. 5]. However, the drop and store approach has several limiting factors, including insufficient space, unsuitable soil types, e.g. rocky soils, high groundwater tables, and poor climatic conditions, e.g., rainy climates [Dra-97, p. 11], [Esr-01, p. 11], as well as the unpleasant job of pit emptying, which makes their users prefer to build new pits when old ones became full, which could be expensive if this practice is repeated every time, especially in urban areas [Wer-03, p. 4]. Therefore, the use of pits is not sustainable over a longer period, even if they are constructed from local materials [Kva-11, p. 4]. Moreover, using vacuum pump trucks for emptying pits and septic tanks is also expensive for poor communities [Win-97, p. 5].

Reuse revenues

In the FlushSan approach, reuse options of treated wastewater are not only financially feasible, but also profitable for operating the WWTP for an extended time [Lng-11, p. 75]. However, the FlushSan mostly needs some manner of subsidy by local municipalities and state government and tax moneys [Kfw-10, p. 13], even in most industrialized countries, because its revenues are insufficient to cover all operation and maintenance costs [Par-14, p. 9]. Asking the emerging countries to cover these high costs is unreasonable [COHRE-08, p. 17]. Therefore, financial aids from international funders, e.g., European Commission and World Bank, and industrialized countries become essential to emerging countries for provision of FlushSan and construction of centralized WWTPs [Mss-09, p. 658], their rehabilitation, and extension of water-borne sewers [Par-14, p. 9]. However, many internationally subsidized treatment plants become overloaded or stop functioning after some years [Ott-03, p. 24] because of lack of funds for operation and maintenance, lack of technical expertise to perform these tasks [UN-Water-15, p. 15], inappropriate adoption of used technologies, and not considering the local conditions, e.g., climate [Mss-09, p. 658]. In addition, they require advanced equipment that typically cannot be manufactured locally [Flo-09, p. 2973]. For the nutrient recovery from faecal sludge that is produced in WWTPs, it has been estimated not to exceed 30% [Crm-13, p. 5485]. Likewise, transport of recovered nutrients from the production location to the end user location can be financially infeasible [Wsh-03, p. 6]. Nevertheless, other benefits of the wastewater reuse options can be achieved in agriculture by securing water for irrigation and by reducing extensive use of chemical fertilizers. These benefits can be translated into cost savings, if side effects of any potential pollution are not considered [Lng-11, p. 68]. Therefore, the economic viability of wastewater reuse is conditional to the level of treatment, differs between regions [Luc-16, p. 973], and requires better assessment [Afi-06, p. 78].

The drop and store approach are not designed for reusing human excrement, however, the stored and buried excrement are reused in agriculture after some time. However, the untreated excrement is commonly reused in most emerging countries [WHO-89, p. 17], to reduce the costs of commercial fertilizers [Esr-98].

2.2.3. Environmental considerations

Sanitation is a core environmental issue. Besides water, sanitation constitutes one of the top drivers of development. Provision of improved sanitation is crucial to human health and the environment. The author sheds light on environmental impacts, and waste and recovery of natural resources as the most important indicators for evaluating the conventional sanitation approaches, primarily flush and discharge and drop and store in terms of the environmental aspects.

Environmental impacts

The FlushSan approach can work well and offer an acceptable level of environment protection if its infrastructure (water-borne sewers and WWTPs) is well developed, operated, and maintained [Til-10], [Kro-16]. However the FlushSan allows a relatively small amount of human excrement to contaminate a huge amount of drinking water by an significant amount of pathogens [Win-97]. In addition, problems that result from discharging untreated or partially treated wastewater cause substantial contaminations to receiving bodies of water [Kha-09, p. 86], [Lib-12, p. 61] by the eutrophication phenomenon. These problems likewise pose serious risks to the environment [Fea-83, p. 90], [WELL-98, p. 68], [Esr-01, p. 10], [Bra-08, p. 216], [Wil-16, p. 150], including fisheries, and livelihoods. Eventually, the food chain is also seriously impacted [Crc-10, p. 5]. In industrialized countries, the laws prohibit discharging of untreated wastewater into bodies of water. Although laws are increasing rapidly with time in emerging countries for discharging untreated wastewater in to the environment [Gag-12, p. 33], the quality and reliability of the conventional FlushSan approach for current and future generations remains questionable in emerging countries [Kha-09, p. 90 f.].

In most emerging countries, unavailability of well-functioning WWTPs downstream at the end of the pipe forces discharging of untreated wastewater into the environment [Esr-01, p. 10], [Gag-12, p. 6]. Approximately 90% of all wastewater (domestic and industrial) is directly discharged without treatment into the bodies of water [UN-CSD-97, p. 14], [Crc-10, p. 5]. Moreover, the inadequate operation of the WWTPs, particularly in emerging countries, presents an obstacle for the accurate determination of wastewater quantities that have been discharged into the environment [UN-Water-15, p. 15]. Due to poor management, the maintenance of current FlushSan infrastructures generally have been neglected, especially those installed underground, e.g., water-borne sewers, for many years, leading to wastewater leakages and crumble of such sewers[Kha-09, p. 90 f.]. The state of the art centralized WWTPs allows discharge of less than 10% of phosphorus into the bodies of water. The remaining 90% is kept in the form of bio-solid waste, e.g., faecal sludge, for further biological treatment and production of soil conditioner [Kie-10, p. 2]. However, some scientists still argue that the potential contamination of water bodies may occur even with low concentration of nutrients and micro-pollutants [Mug-08, p. 437].

From another point of view, the drop and store approach could have a negative impact on the environment, as full pits and septic tanks need emptying, desludging, and transporting for dumping into bodies of water without treatment due to lack of treatment plants and institutional regulations, which are common practices in most emerging countries [UN-Water-15].

Waste of Natural resources

In the FlushSan approach, a regular water supply is an inevitable requirement for operation, as the water is used to transport human excrement from its production location to the location of either disposal or treatment [Esr-01, p. 10], [Ott-03, p. 24]. The use of more than 15,000 litres of drinking water per person annually to flush only the 50 litres of faeces and 500 litres of urine for the person is an unwise and irrational use for the valuable water resource [Esr-01, p. 10]. Moreover, the water consumed by FlushSan may be greater than that used for drinking, irrigation, and industrial purposes [Wil-16, p. 140], which tends to increase by rapid growth of population, urbanization, and increased living standards, and depletes the natural resource

[Wer-03, p. 4]. This might make drinking water an unaffordable or expensive commodity in the future, particularly in countries that are facing problems of water scarcity [Ott-03, p. 24]. Water scarcity force provision of the FlushSan approach to rich people only in most emerging countries [Win-97, p. 4], [COHRE-08, p. 17]. Most industrialized countries have established several approaches to FlushSan to reduce water consumption, e.g., reusing treated wastewater, at-source minimizing wastewater, and high-efficiency water-saving plumbing fixtures, e.g., toilets, urinals, and washbasins, that were recently brought to the markets [Kro-16, p. 92]. [Grn-12] and [Wlm-13] have reviewed some of these emerging approaches for reducing water consumption in the FlushSan approach. Although reduction of water consumption in FlushSan has positive effects on water scarcity, other components of FlushSan, e.g., toilets, water-borne sewers, and electrical pumps, could be negatively affected [Jac-00], [Kau-07], [PERC-09]. Since the 1960s, the FlushSan depends on the nutrient removal from the wastewater [NSF-04, p. 6] as a standard treatment principle. The nutrient removal requires relatively large amounts of energy and chemical resources [Wsh-03, p. 1], [Dai-09, p. 809]. For instance, the removal of nitrogen requires about 45 megajoule (*MJ*) per *kg* nitrogen to release it into the atmosphere in a gaseous form [Xie-16, p. 210].

Commonly, in drop and store approach, pits are poorly designed or inaccessible for emptying—then they become abandoned [UN-Water-15, p. 16]. The faecal sludge that is separated from liquid wastewater and stored in septic tanks have nowhere to be safely disposed and commonly are discharged into the environment without treatment [Par-14, p. 9]. Moreover, the liquid wastewater is allowed to flow on the surface either to evaporate in the atmosphere or to infiltrate into the sub-soil to join groundwater [Wer-03, p. 4] if the water table is high [Jan-06, p.32], [Ort-07, p. 260]. These improper practices lead to losing of valuable nutrients [Dra-97, p. 11]. However, the drop and store approach requires no electricity [Dod-12, p. 3709] and uses less water compared to the FlushSan approach [Par-08, p. 34].

Recovery of Natural resources

Currently, a concrete consensus exists for considering treated wastewater as a valuable renewable resource. The most significant environmental benefits that are manifested in treating the wastewater are saving available water resources [Lng-11, p. 69], closing the water cycle, and preventing contamination of bodies of water [WHO-89, p. 17], [Mor-16, p. 4741]. However, the reuse options require a thorough assessment and restricted standards to eliminate potential risks to the environment [Afi-06, p. 77]. To this end, WHO has prepared a new guideline with "*more realistic bacterial indicator value*" including parasitic worms "*a helminth egg guideline*", as the helminth infections reduce the quality of effluent and limit the reuse options [WHO-89, p. 13].

The FlushSan approach deals with plant nutrients, nitrogen (N), phosphorus (P), and potassium (K), as wastes and not as valuable resources [Sct-05, p. 8], [Flo-09, p. 2973]. FlushSan has broken the closed loop for these nutrients [Lüt-09, p. 452], and the nutrient recovery becomes an almost impossible task for the majority of currently applied removal equipment in WWTPs [Wsh-03, p. 2 f.], [Vrt-09, p. 5537]. This is likely due to the dilution of nutrients in the flushing water [Lüt-09, p. 452] by a factor of more than 100 before reaching the treatment plants [Wsh-03, p. 2 f.].

Although, the drop and store approach is not designed for nutrient recovery, incorporation of reuse option of the bio-solid wastes within the drop and store approach is a feasible alternative to the FlushSan approach in emerging countries. However, sufficient health precautions and measures should be taken into consideration [Psy-00, p. 12], specifically during emptying and disposal of pits and septic tanks [Kfw-10, p. 13].

Currently, several advanced technologies exist for nutrient recovery, which can be implemented either in centralized or decentralized sites [Dai-09, p. 809]. Recent studies on nutrient recovery processes and equipment are provided by [Xie-16], [Vrt-09], [Kim-16], and [Neo-16]. However, many scientists still believe in the urgent need for replacing the current sanitation approaches by the resource-oriented approaches that are able to recover, recycle, and reuse natural resources to meet the economic, environmental, and social sustainability [Wsh-03, p. 1], [Dai-09, p. 809], [Gue-09, p. 6127], [Fac-10, p. 2673].

3. Sustainable sanitation and decentralized management of wastewater

3.1. Sustainable sanitation approach

Development of sustainable sanitation, provision of water supply, and promotion of adequate hygiene have been globally significant concerns due to their consequences on human health and the local environment. Sustainable sanitation requires extensive and intensive efforts from all segments of the community [Chn-12, p. 233].

3.1.1. Definition

To meet essential human needs for sanitation was one of the critical objectives of the sustainable development concept that was disseminated to include the social, economic, and environmental dimensions in the Brundlandt report in 1987 [Bru-87] and the United Nations Conference on Environment and Development, which was held in Rio de Janeiro in 1992. On this basis, [Lüt-09] defined sustainable sanitation as:

> *"The one that meets the basic sanitation needs of all population segments of the present generation within a city (principle of equity) without compromising the present and future generations living inside and outside of the city to meet their own needs."*

The Sustainable Sanitation Alliance (SuSanA) [SuSanA-08] also gives a generic definition of sustainable sanitation:

> *"The main objective of a sanitation system is to protect and promote human health by providing a clean environment and breaking the cycle of disease. In order to be sustainable, a sanitation system has to be not only economically viable, socially acceptable, and technically and institutionally appropriate, it should also protect the environment and the natural resources."*

Considering the concept of sustainability as not a stage or point that needs to be reached but as a direction or approach, sustainable sanitation is deemed as a specific context, and no sanitation approach is absolutely sustainable" [SuSanA-08], [Len-09]. Therefore, to be sustainable, a sanitation approach requires a holistic planning and decision-making process [Lüt-09, p. 456], which should take into consideration all actions that are required to adequately manage all human wastes[SuSanA-08, p. 6]. Key steps can be taken toward achieving sustainable sanitation, including bring about a change in attitude regarding human excrement and water use [Rsm-05, p. 112]; incorporate sanitation within the agricultural activities that accept water and nutrient reuse [Ott-01, p. 3], [Mei-10]; and integrate sanitation with sustainable water resources and the ecological environment [Nak-06, p. 1093]. Moreover, a good monetary and social investment can be achieved by adapting the concept of sustainable sanitation to local conditions, e.g., climate [Lüt-09, p. 460].

3.1.2. Principles and objectives

There is a consensus about the general principles of any sustainable sanitation approach that must protect human health and the local environment. This could be accomplished by excluding all untreated human excrement and wastewater from being disposed of into the environment [Chn-12, p. 234]. The essential features of a sustainable approach include managing human wastes via treatment, recycling, reusing of their potential resources [Kuj-06, p. 115], and preventing contamination, contrary to conventional approaches that fail to comply with all these features. Other important features also encompass closing water and nutrient cycles, considering local resources and ecosystem, infrastructure decentralization, and equitable service for all [Rsm-05, p. 112].

Four fundamental principles for sustainable sanitation that are addressed in [Mar-07] are human health, affordability, environmental sustainability, and institutional appropriateness. The human health principle states that the sanitation approach should improve human health, and it must not create any harmful circumstances to humans. The affordability principle asserts that the poor and very poor users must be able to afford the construction, operation, and maintenance of the sanitation facilities. The environmental sustainability principle indicates that the sanitation approach must not have a negative impact on the environment, and must include the appropriate treatment of human wastes to a level that enhances their reuse in agricultural activities. Institutional appropriateness means that the sanitation approach should be managed at the appropriate level by involving the entire community in its planning, implementation, operation, and maintenance; and by considering the different demands of the gender (men and women) and different views and needs of the poor and rich people. These principles should also agree with the Bellagio statement on environmental sanitation [Sct-00], which should be carefully observed during the planning and implementation of such an approach [SuSanA-08].

Sustainable sanitation requires addressing of not only a certain technological component, i.e., process or equipment, but also cost, ownership, and needed space [Kat-12, p. 965]. This means that the technology should be feasible, affordable, and accepted by the user [Kat-12, p. 966].

According to [SuSanA-08], the most inclusive and indisputable objective of a sustainable approach is to "protect and promote human health by providing a clean environment and breaking the cycle of disease".

The common specific objectives of the sustainable approach, as identified by several scientists and experts [Bha-01], [Nak-06], [SuSanA-08], are as follows:

- Protecting the human health of the entire community.
- Protecting the local environment by preventing negative impacts to its area of implementation upstream and downstream.
- Reducing water use.
- Recycling and reusing nutrients.

Further specific objectives as listed by [SuSanA-08] are:

- Optimizing the entire approach on a social, technical, and legal basis and considering the necessary trade-offs.
- Making the approach economically viable for its users and the community.
- Ensuring its flexibility to future expansion and demand.

Based on the local conditions, other site specific objectives could be:

- Improving urban drainage.
- Reducing energy consumption as much as possible.
- Obtaining renewable energy through wastewater treatment.

3.1.3. Concept of resource-oriented sanitation

Wastewater can be considered a valuable resource for water, energy, and materials in the form of nutrients. Water can be recovered after treatment and used for additional water quantities for areas that suffer from water scarcity. Energy can be recovered as biogas that can be produced by assimilating the bio-solid wastes through a biological anaerobic treatment, while material (nutrients) can be recovered by converting the wastewater bio-solid wastes into soil conditioner or compost. On this basis, a paradigm shift in sanitation can begin by admitting that wastewater has valuable resources, and its sustainability depends primarily on not wasting these resources, even if they are safely disposed of or dumped, and determining how to recover these resources [Gue-09, p. 6127].

Resource-oriented sanitation approach (ROSA) [SuSanA-08] introduces sanitation to water and natural resource sustainability [Wer-09, p. 394]. ROSA is an alternative approach that attempts to avoid drawbacks of the conventional sanitation approach. It can be defined as a holistic concept or a systematic approach for closing water and nutrient cycles with the least amount of materials and energy costs as possible through interlinking sanitation with agriculture. In addition to meeting the sanitation needs, i.e., fulfilment of the hygiene requirements during handling and reusing of human wastes [Ott-11], [Bul-13]. ROSA also considers available technological components as only a means to an end as they may range from a single process or equipment, e.g., compost toilets, to a sophisticated combination of several processes and equipment, e.g., WWTPs. To meet most social and economic conditions, these components may range from low-tech to high-tech; simple to complex; and decentralized to centralized approaches. Therefore, in view of ROSA, the development of a certain sanitation approach can be achieved by combining and selecting its components from the entire range of available conventional and unconventional components. These components may not be "ecological per se" but should be assessed for the specific environment where they can be used [Lan-05], [Vli-10, p. 2].

Today, ROSA and "ecological sanitation" are similar concepts in considering wastewater as a valuable source that needs to be recovered, recycled, and reused by interlinking to agriculture [Wer-09], [Lan-13]. However, to be sustainable, ROSA should comply with the sustainable sanitation objectives [SuSanA-08].

[Lüt-09] argued that the sustainable approaches may consist of decentralized and resource-oriented concepts, including nonconventional technological components, e.g., constructed wetlands or biogas reactors. Moreover, on contrary to centralized sanitation approaches, the decentralized approaches have more flexibilities in wastewater management and combination between different processes and equipment that can be arranged to achieve a specific treatment goal. Decentralized sanitation approaches are not only long-term solution for small communities but also have reliable treatment efficiency and cost effective. But it needs studying the observed environment and selection of technological components based on a comprehensive evaluation for each specific site[Mss-09].

In line with the scope of this thesis, the following sections include a part of literature review and some case studies on some nonconventional technological components, including pre-treatment equipment, constructed wetlands, and Terra Preta sanitation processes. These components were selected and adopted to develop a decentralized resource-oriented sanitation module based on ROSA requirements for managing the liquid waste and bio-solid wastes at a household level in emerging countries.

3.2. Pre-treatment process

3.2.1. Overview on pre-treatment

A pre-treatment for liquid waste, i.e., greywater or blackwater, called also the primary treatment or solid-liquid separation process [Hof-10]. Pre-treatment is the preliminary removal of wastewater solids, e.g., oil, grease, sand, fibres, and trash, as well as some organic matter from the liquid waste [Til-14]. Pre-treatment is necessary for most biological treatment modules [Ott-99]. Pre-treatment equipment can remove the solids, postpone their accumulation, and minimize subsequent blockages in the secondary treatment equipment [Gag-12], e.g., constructed wetlands [Hof-11, p. 18]. The higher the level of pre-treatment, the lower the amount of secondary treatment is required [Fer-03]. Other benefits of pre-treatment equipment are reduction of corrosion in mechanical parts of secondary treatment equipment and hence increased durability of these sanitation facilities and an extended lifespan [Til-14]. Pre-treatment has been proven useful for wastewater, which contains small amounts of biodegradable organics and large amounts of non-biodegradable material, or what are called recalcitrant compounds [Neo-16].

Pre-treatment equipment uses physical removal mechanisms e.g. screening, flotation, settling, and filtration. Several types of equipment are used for separation of solid from liquid, including screening chambers, grease traps, grit chambers, and sedimentation tanks [Gag-12], [Til-14]. Table 3-1 provides an overview on pre-treatment equipment. Pre-treatment equipment that depends on screens, seals, and filters is commercially available in markets. This commercial equipment is useful in large wastewater treatment facilities and in other special applications, e.g., drip irrigation. For household applications, this type of equipment is seldom used because it is not cost effective nor sufficiently reliable. However, the homemade seals and filters that rely on gravel may be appropriate for small-scale and household applications [Win-04].

Table 3-1: Overview of solid-liquid separation equipment, applications, and scale [Hof-10], [Hof-11].

Pre-treatment equipment	Greywater with low organic load	Domestic wastewater or greywater with high organic load	Scale (*p.e.)*
Screens	x	x	>1,000
Grit removal chamber	x	x	>1,000
Grease trap	x	x	At household level
Septic tank		x	5-200
Baffled tank		x	200-2,500
Imhoff tanks		x	500-20,000
Up-flow anaerobic sludge bed		x	>5000
Compost filter "Rottebehälter"		x	Up to 70

Considering household or small-scale applications, some pre-treatment includes conventional equipment, e.g., Imhoff tanks, septic tanks [Bri-07, p. 2], and grinder pumps [Fer-03], and nonconventional equipment, e.g., compost filter or “Rottebehälter” as called in German [Gaj-03].

In pre-treatment equipment, e.g., Imhoff tanks, septic tanks, anaerobic conditions are common, and cause stabilization of organic matter and reduction in sludge quantities. This give the possibilities for subsequent recovery of biogas, while the stabilized sludge can be used as manure [Nha-04]. Moreover, aerobic conditions in a variety of pre-treatment equipment have been used in recent years [Fer-03], with compost filters [Hof-11] as one example.

After separation of settleable solids, liquid effluent has a lower load of organics [Nha-04] and can be treated in constructed wetlands [Kuj-06] as well as in other conventional and nonconventional biological modules, via soil filtration beds [Buu-99], biofilm modules, e.g., trickling filters, and activated sludge with filtration, e.g., membrane bioreactors or biological filters [Jef-00], [Neo-16].

In line with the scope of this thesis, this section provides a brief overview of the pre-treatment process, septic tanks as conventional pre-treatment equipment, and compost filters (Rottebehälter) as nonconventional equipment. For further details about different types of pre-treatment equipment, the reader may refer to [Gry-04] and [Til-14], and for the basic design equations of septic tank, baffled tanks, and Imhoff tanks, refer to [Gut-09].

3.2.2. Pre-treatment equipment before constructed wetlands

Generally, wastewater contains solids and liquid wastes. Solids should be removed from the liquid waste before allowing them to enter the treatment modules that depend on nature for purification of liquid waste, e.g., soil filtration beds and constructed wetlands. This initial separation is crucial, because solids can accumulate and form a faecal sludge in free pores of filtration media. This accumulation of solids eventually causes clogging of vegetation beds [Hof-11, p. 18]. The need for removal of solids relies on how these solids and liquid wastes will later be treated and used [Win-04]. Pre-treatment is an essential requirement in case constructed wetlands are used for secondary treatment purposes [Par-03], [Mas-07]. See section (3.3) for more details on constructed wetlands.

Using an efficient equipment for solid removal before a liquid waste enters the constructed wetland can improve the overall treatment efficiency and reduce wetland space area needed for its construction, especially in wormer climates areas [Gar-03]. The user must not come in direct contact with both influent and effluent of pre-treatment equipment because they contain high content of pathogens. Therefore, the equipment should be well controlled and regularly inspected to ensure that it works properly, and it must be emptied frequently. A proper emptying process, either by skilled labourers or motorized equipment, e.g., vacuum pump truck, can decrease the health risks[Til-14]. Then, the settled solids that are emptied should be treated in a healthy and safe manner in drying beds or composting facilities [EAWAG-14].

3.2.3. Septic tanks

The common subsurface disposal module for handling household wastewater consists of a septic tank as pre-treatment equipment and a leaching bed for additional treatment of septic tank effluent [Brn-78]. Septic tanks are widely used for on-site wastewater treatment because of their simplicity in construction, particularly in emerging countries [Hof-10] or where connection to main water-borne sewers is not available or is impractical and costly [Dud-07].

Septic tanks or their advanced versions, up-flow anaerobic sludge beds and anaerobic baffled reactors, are considered an efficient and reliable pre-treatment equipment for most wastewater treatment modules in rural as well as urban areas [Win-04], [Kuj-06], [Til-14].

Septic tanks are watertight chambers and can be made of concrete, fibreglass, plastic, or PVC. In septic tanks, solids typically are removed by sedimentation at the bottom of the tank as faecal sludge, and by floatation at the top as scum [Bod-07], [Til-14], as shown in Figure 3-1.

Over time, the accumulated faecal sludge has a reduction in its volume due to the anaerobic degradation. However, the degradation rate is lower than the settling and accumulation rates. Hence, faecal sludge and scum must be frequently and periodically removed from these tanks [Oxfam-08], [Til-14].

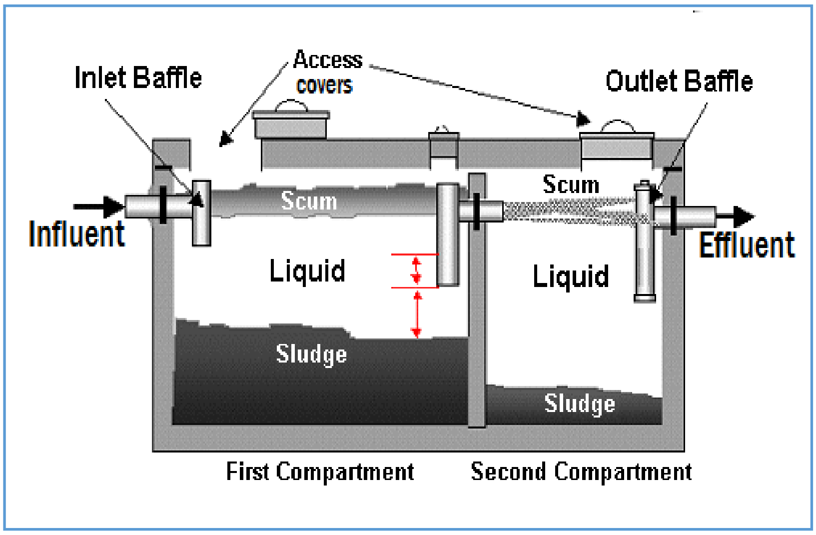


Figure 3-1: Cross-section schematic of typical double-chamber septic tank. Reproduced from [KCBH-16]

Septic tanks are designed for hydraulic retention time of 1-2 days in warm climate areas and up to 5 days in cold climate areas [Hof-11]. Well-designed and maintained septic tanks have a typical removal of 30-40% of organic matter, measured as biological oxygen demand at 5 days (BOD_5), 50% of total suspended solids, and 1 log unit of faecal bacteria, measured as *Escherichia coli* (E. coli.) However, their removal efficiencies vary significantly depending on the organic matter content in wastewater, household use of chemicals [Brn-78], operation, maintenance, climatic conditions [Til-14], tank condition, number of users, and water use of users [Rds-16].

Under normal operating conditions, septic tanks do not need electrical energy and do not expose users to direct contact with their influent or effluent of wastewater. However, during maintenance and emptying, effluent, sludge, and scum must be handled with high care due to their high content of pathogens. Septic tanks should be regularly monitored to check whether they are functioning well. Generally, septic tanks are emptied every 2-5 years [Oxfam-08], [Gut-09], [Til-14]. For more details about septic tank design, see [Oxfam-08]; septic tank performance and process, see [Bou-97] and [Bea-05]; and septic tank problems and practices, refer to [But-95].

3.2.4. Compost filters

Compost filters, also called pre-composting tanks or "Rottebehälter "in German, act as solid-liquid separation equipment [Hof-09] in which wastewater solids are retained in a special filter bag and wastewater liquid is drained to a certain extent by passing from the filter bag to the bottom of the compost filter. The retained solids must have further treatment via, e.g., composting, before direct application in farmlands. Organic “kitchen” waste can be added to retained solids during the composting process. The effluent liquid must be additionally treated, in e.g., constructed wetlands, before discharging into nearby bodies of water or reuse in irrigation [Gaj-03], [Hof-10].

Compost filters are relatively new equipment that are considered an interesting and novel alternative to conventional pre-treatment equipment in decentralized sanitation approaches [Gaj-03], [Hof-11]. Major advantages of composting filters to other equipment, e.g., septic tanks, are that it does not require expensive emptying means via skilled labour or motorized equipment, and valuable nutrients of human excrement are not wasted and are made available as soil conditioner for reuse in agriculture after having additional treatment. Compost filters in combination with constructed wetlands have been increasingly used in rural areas in Germany, Austria, and Switzerland [Gaj-03].

A compost filter consists of a subsurface concrete tank in which two filter bags are hung side by side and used alternatively every 6–12 months, as shown in Figure 3-2 (a) and (b). The filter bag that is being used is called the active bag, while the filter bag that has been used already is called the inactive bag. The retained solids in the inactive bag can be stored inside the tank for another 6–12 months until the active bag becomes full [Gaj-03]. Then, the inactive bag should be removed from the tank for further treatment via, e.g., hot composting or vermicomposting. During the storage time inside the tank, the inactive bag solids are composted, and a reduction in their volume can reach up to 75% [Hof-10]. The liquid that passes from filter bags can be collected below the filter bags at the bottom of the tank. The liquid effluent can be discharged from the tank by electrical pump to a secondary treatment module or it can flow directly by gravity if ground slope helps [Gaj-03], [Hof-10].

Inside the active filter bag, dry bulking agent, e.g., straw or bark, has to be added on a weekly basis to reduce the moisture content of solids, which can maintain an aerobic condition and prevent an offensive odour [Hof-10], [Hof-11]. The addition of dry bulking agent may cause more loss of the organic matter compared to when not added. However, addition of sufficient amount of this bulking agent is required for the composting process, because it improves carbon to nitrogen C:N ratio and moisture content, and it circulates air for pre-composted solids, which are necessary parameters for the composting process. Moreover, further investigation to determine the suitable quantities of bulking agent is required [Gaj-03]. However, an anaerobic condition might occur, especially in the inner portion of the solids as the outer portion has regular contact with air and no offensive odour is noticed by users [Gaj-03]. Another case study by [Hof-09] revealed that after 2–3 weeks without straw addition, an offensive odour began to smell near the compost filter [Hof-09].

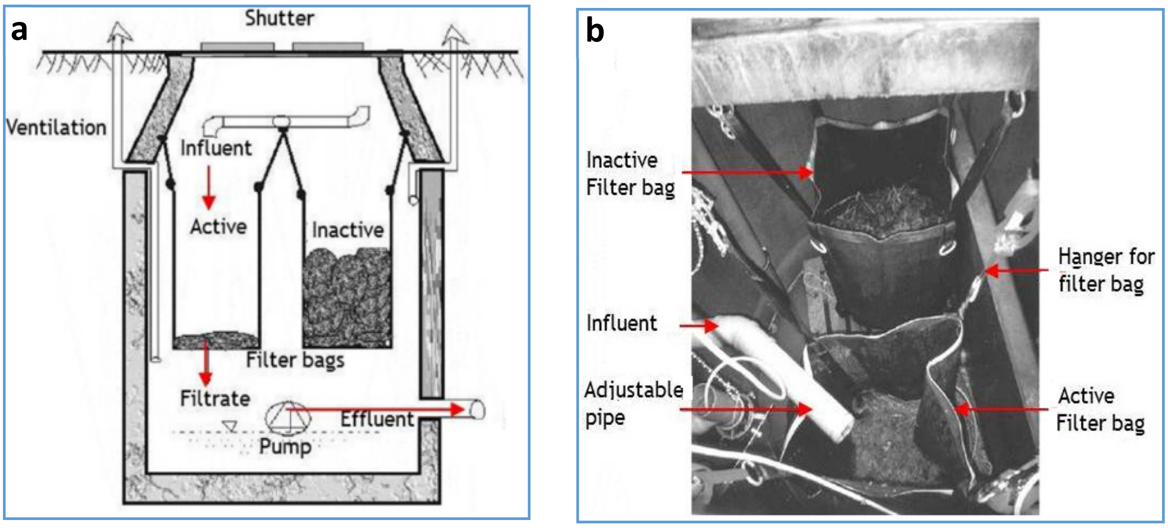


Figure 3-2: (a) Cross-section schematic of compost filer; (b) Compost filter and filter bags. Reproduced from: [Gaj-03]

The compost filter can be most appropriate equipment for areas where there is a need for the reusing products, i.e., soil conditioner and treated water. The compost filter can be used to serve from 4–40 people [Gaj-03], or even up to 70 people. Based upon the number of users, 2–4 filter bags can be hung and used alternatively in two separate chambers [Hof-11].

[Gaj-03] evaluated five compost filters in Germany and noticed that all filters were working for 4-5 years without any operational problems. Results of his evaluation revealed that retained solids still contain a high percentage of water [Gaj-03], which must be lowered to optimal levels of 50–60% for the composting process [Eps-97]. Necessary measures for preventing a heat loss and maintaining a good ventilation inside compost filters are important for effective performance [Gaj-03]. The maintenance of such equipment is crucial and requires improvements during removal and handling of retained solids, because it relies mostly on labour. In addition, high health care measures must be taken into consideration to avoid human contact during handling and removal of retained solids or addition of straw. Other disadvantages of compost filters include:

- Their capacity is limited to a small number of users up to 70 persons.
- They work only with highly concentrated blackwater, because many solids may be washed out from the active bag [Hof-11].
- The long use period of 6–12 months may cause washing of nutrients from active bags.
- Offensive odour may be smelled if straw or other dry bulking agent is not added regularly to the active bag, and if bad ventilation has occurred.
- Clogging in filter bag may occur if the wrong filter bag is selected, maintenance is bad, or the incorrect dry bulking agent is used [Str-16].

3.3. Constructed wetlands

3.3.1. Overview on constructed wetlands

Constructed wetlands (CWs) are typical engineered treatment equipment that are mainly designed and operated as a biological sand filtration bed. The treatment of variety of liquid wastes, including domestic wastewater depends on natural principles by involving wetland vegetation, filtration media, and associated microorganisms' colonies. The use of CW has rapidly increased since the mid-1980s [Ree-93]. They have proved to be a suitable treatment option in urban, suburban, and rural areas of European countries [Bav-95]. CWs can be used as part of a decentralized sanitation approach [USEPA-04, p. 21] as well as in centralized approaches or where a sanitation approach relies on water for flushing human excrement [Ana-14, p. 331]. Contrary to their usage as secondary treatment equipment in decentralized approaches, CWs are increasingly used as tertiary treatment equipment in conventional wastewater treatment plants after activated sludge, rotating biological contactor, upflow anaerobic sludge blanket digestion UASB [Mas-07], [Rou-08], or trickling filters [Hof-11].

3.3.2. Types and flow patterns

CWs are generally subdivided into two main types based on how influent liquid flows into these wetlands: surface flow and subsurface flow CWs. A hybrid module can be developed by incorporation of surface flow and subsurface flow wetlands [Dav-95].

Surface flow or free water surface (FWS) wetlands mimic the hydrologic regime of natural wetlands and marshes [Ell-03], in which wastewater flows on the surface through a shallow basin planted with emergent, submergent, and/or floating macrophyte plants [Hof-11]. In FWS, the liquid surface is above the filtration media. The layer of filtration media near the surface is aerobic, while deeper layers are anaerobic. Rather than performing water treatment, FWS can maintain a wildlife habitat and provide aesthetic views. FWS are often utilized to treat storm water, mine drainage, and agricultural runoff [Dav-95].

Subsurface flow (SSF) wetlands consist of a sealed bed filled with a gravel, sand, or similar substrates. The influent liquid is designed to flow below the surface of the filtration bed. The beds are often planted with emergent (aquatic) plants that are commonly found in natural wetlands or non-submerged riverbanks. SSF wetlands can be subdivided into two types based on the influent liquid flow configurations: horizontal flow (HF) and vertical flow (VF) [Ell-03], [Mas-07], [Hof-11], [Til-14].

In HF wetlands, the influent liquid enters the wetland bed through an inlet and then flows slowly through the filtration media in generally horizontal path to the outlet side [Ell-03], [Hof-11], as shown in Figure 3-3(a). The filtration media works as a filter to remove solids; a fixed surface is provided for microorganisms to attach and degrade organics [Woo-95]; and a base exists for vegetation to grow [Til-14].

In VF wetlands, the influent liquid is intermittently poured or fed onto the surface from above via a mechanical dosing equipment. The liquid then seeps vertically down through the filtration media to the bottom of the bed, where it is collected by a drainage pipe. The VF often have a sand layer on the top to overlie the filtration media [Ell-03], as shown in Figure 3-3(b).

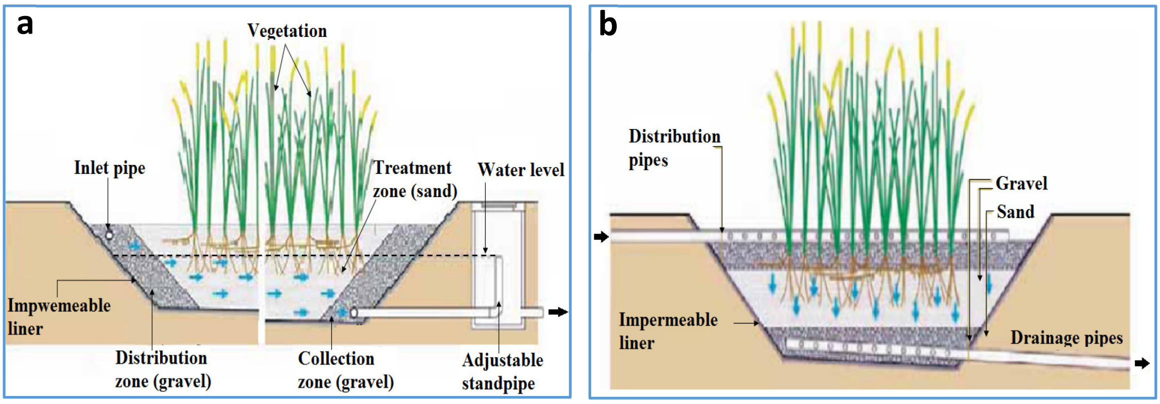


Figure 3-3: Schematic cross-section of (a) HF wetland; (b) VF wetland. Reprinted from: [Mor-06]

The difference between HF and VF wetlands is not only in the direction of the liquid flow in the filtration media but also in the biological conditions, e.g., aerobic and anaerobic [Til-14]. In addition, VF wetlands have higher treatment efficiencies compared to HF wetlands, which require as much as double the space. Although the space requirement is a limiting factor for CW implantation in most urban areas due to the land availability and cost, VF wetlands can be small enough to fit into the available space. This also makes HF wetland implementation an unfeasible solution in most urban areas [Hof-11, p. 8].

Different types of CW can be combined together or combined with other low-tech or high-tech treatment options to form a hybrid system to benefit from specific advantages of each type [Hof-11, p. 9], [Rou-08, p. 182].

3.3.3. Performance and purification processes

Purification processes in CWs are similar to physical, chemical, and biological processes that occur in nature, i.e., soil and bodies of water [USEPA-97, p. 4], including filtration, sedimentation adsorption, biological degradation, photolysis, nitrification, denitrification, microbial uptake, plant uptake, and volatilization [UN-HABITAT-08]. Purification occurs during the contact of influent liquid with the plant roots and filtration media surfaces, which change from being unsaturated to saturated long enough to maintain emergent plants, e.g., reeds, bulrush, and cattails [USEPA-04, p. 15].

The key factors that affect the CW treatment efficiency are as follows:

- Types of filtration media, which must have an adequate hydraulic conductivity and a high capacity of nutrients sorption, e.g. gravel [Bas-04, p. 4228].

- Type of vegetation, e.g., emergent aquatic macrophytes, which is an essential part of CWs and has a fundamental role in wastewater treatment [Hof-11, p. 14], because it can make channels in the filtration bed and maintain permeability of filtration media [Koo-05], [Til-14]; and to provide a fixed surface for microorganisms to agglomerate and colonize, which is mainly responsible for the treatment via nutrient adsorption and organic degradation and stabilization [Woo-95], [Til-14]. In addition, they can remove nutrients indirectly through up-taking them as ions, e.g., phosphorus [Bas-04].
- Microorganisms colonies, which survive in the vegetation bed and can degrade the organics that are absorbed by roots of plants [Bas-04, p. 4227]. Therefore, the interaction of plants and those microorganisms is one of the secrets for purification and pollutant removal in CWs [Koo-05, p. 120].

CW purification capability and mechanisms for different types of pollutants in wastewater is described in the following paragraphs.

Organic matter removal

Degradation of organics in wastewater is measured by BOD_5. The removal of BOD_5 occurs rapidly when organics settle and entrap in the void spaces of filtration media in SSF beds. The soluble BOD_5 is removed by the microorganisms. However, a complete removal of BOD_5 cannot be achieved by CWs, and residual BOD_5 from 2 to 7 mg/l typically exists in the effluent liquid [Ree-93].

In HF wetlands, anaerobic and facultative bacteria are responsible for degrading most organics. However, aerobic bacteria can also be colonized at the plant roots and rhizomes zones, and they can remove BOD_5, where a small amount of oxygen is transferred by plant leafs to roots [Til-14, p. 116].

In the VF wetlands, as dosing of wastewater is not continuous, the filtration bed goes through saturation and unsaturation phases. Accordingly, different phases of aerobic and anaerobic conditions would occur. During the dosing phase, the wastewater infiltrates vertically down through the unsaturated layer and the bed drains, air is drawn into it, and the oxygen has time to diffuse through the filtration media. Similar to the HF wetlands, plants transfer a small amount of oxygen from leaves to roots. The discontinuity in dosing of liquid forces the microorganisms into a starvation phase. Therefore, excessive biomass concentration can be reduced and porosity of filtration media can be increased [Til-14, p. 118].

Nutrient removal

The SSF wetlands are primarily designed to remove suspended solids to achieve effluents with very low concentrations [Ree-93]. They have high nutrient removal capabilities [Bir-93, p. 19 f.]. Nitrogen (N), as one of the main nutrient elements, is potentially removed to very low levels if sufficient detention time and oxygen to support the necessary nitrification reactions are available. The nitrogen removal is of a high concern in wastewater treatment due to its toxicity for fish and other aquatic animals. However, phosphorus (P) removal is limited, and supplementary treatment are necessary [Ree-93].

Pathogen removal

In the SSF wetlands, a significant pathogen removal, e.g., faecal bacteria, is carried out by natural decay, predation by highly colonized microorganisms to less colonized ones, and filtration. As wastewater flows below the surface, any potential contact of human and wildlife with pathogenic organisms is minimized and the risk of flies breeding, e.g., mosquitoes, is reduced because no stagnant water is on the surface [Til-14, p. 119]. SSF wetlands have reliable treatment efficiencies for pathogen removal compared to conventional high-rate aerobic treatment equipment, e.g., trickling filters, activated sludge plants, rotating discs, submerged aerated filters, and membrane bioreactor plant [Hof-11].

Pathogen removal in SSF wetlands has been related to environmental factors such as hydraulic retention time (HRT), types and size of filtration media, type of emergent aquatic macrophytes [Ree-93], [Gar-03, p. 2646], climatic conditions, e.g., temperature, equipment design, and hydraulic and organic loading rates [Bri-07]. For instance, when the HRT is approximately three days, the pathogens removal level reaches its saturation values, which depend on the filtration media contained in the bed. This means that any increase in the HRT over three days may not result in significantly higher levels of pathogen removal. Moreover, smaller-sized particles (2-13 mm) of filtration media are more efficient in pathogen removal [Gar-03, p. 2652]. Nevertheless, in case the removal level of pathogens does not comply with standards of safe disposal and reuse in agriculture, a final disinfection for effluent liquid is a significant issue [Ree-93].

3.3.4. Treatment applications and case studies

With respect to treatment of wastewater and making it available for reuse as an alternative source of non-potable water, CWs can reduce the cost of both transport and treatment at the WWTPs. Moreover, they can contribute to closed water and nutrient cycles.

Table 3-2 represents the CW capabilities for pollutant removal in domestic wastewater. A study by [Poy-13] concluded that if a small-scale VF wetland is used to treat 350 *l* of greywater per day, about 47% of treated water can be available for reuse in irrigation. The pollution removal efficiency of this VF wetland in the first three months reached 95.5% of BOD_5, 81.1% of chemical oxygen demand (COD), 79.2% of total dissolved solids (TSS), 65% of ammonium ion (NH_4^-), and 99.1% of faecal coliform (FC) bacteria [Poy-13].

Table 3-2: CWs capabilities for pollutant removal in domestic wastewater.

Configuration	Pre-treatment	*p.e.*	Inlet flow	COD	BOD	TSS	NH4+ (TKN)	TP	FC	Ref
			m^3/d	%	%	%	%	%	%	
HF + VF wetlands	Imhoff tank	140	7-33	93.9	95.1	84.6	67.9	94.1	99.97 (3 log)	[Mas-07]
HF wetlands	Septic tank	27	1.5-2.4	81.2	78.8	49.7	54.5	-	99.99 (4 log)	[Afi-13], [Afi-15]
HF wetlands	Septic tank	100	10	87	89	92	73	-	99.999 (5 log)	[Sha-13]
VF wetlands	Imhoff + baffled Tank	100	2-8	85.4	90.5	68.4	60.8	81.1	99.99 (4 log)	[Mas-08]

CWs have several applications for treating various types of wastewater, including municipal and domestic wastewater, blackwater, greywater, and sludge dewatering. CWs have other potential applications for management of landfill leachate, mine drainage [Ree-93], agricultural and urban runoff, and highway run-off [Mas-07], as shown in Table 3-3

Table 3-3: Treatment applications of constructed wetlands for various types of wastes.

Pollution type	Application	Case study/project	Reference
1-Point-source pollution	Municipal wastewater treatment	Gadenstedt, Germany [presented as a project of world exhibition Expo 2000,][serves 3000 people]	[IVeV-16]
		Shenyang, China [serves 6000 people]	[IVeV-16]
	Decentralized and household wastewater treatment	Silkerode, Germany [serves 500 people]	[IVeV-16]
		Bani Suheila, Gaza Strip [serves 20-35 people]	[Afi-13]
	Greywater treatment	Puducherry, India [serves 5 people]	[Poy-13]
	Industrial wastewater treatment	Changshu, China [area 20.000 m²]	[IVeV-16]

		Rafah, Gaza strip	[Nas-06]
	Tertiary treatment of effluents of conventional wastewater treatment plants treatment	Münstedt, Germany [serves 4000 people]	[IB -08]
	Natural swimming pools	Swimming pool Göttingen (Germany) [for public use]	[IB -08]
2-Diffuse pollution	Agricultural and urban run-off	Essex, southeast England [in area of 2000 houses]	[Shu-97]
	Storm water treatment and temporary storage	Oberg, Germany [area 5.600 m²]	[IVeV-16]

Another study by [Afi-13] showed effective treatment of domestic wastewater by a HF wetland that was used as secondary treatment equipment and arranged with a septic tank as a pre-treatment equipment in the Gaza strip. Results indicated that the wetland was able to achieve average removal of 81% COD and 79% BOD in the first three months of the operation phase. The FC average removal reaches 4 log units (99.90%) [Afi-13]. These results can represent the high capabilities of SF wetlands in treating domestic wastewater and providing treated water with accepted quality for reuse in agriculture. Nevertheless, further investigation and research into their design and performance in specific locations is needed, although much research has been conducted on CW performance [Nas-06, p. 28]

3.3.5. Evaluation of constructed wetlands

Evaluation of constructed wetlands have been performed by many authors since their use began in the mid-1980s. Table 3-4 shows the main advantages and disadvantages of CWs with respect to sustainability dimensions, including social issues that are concerned with the CW impact on human health, and their acceptance by the public and communities. The economic dimension concerns the financial aspects of construction, operation, and maintenance, while the environmental concerns address its impact on the local environment.

Table 3-4: Pros and cons of constructed wetlands.

Criteria	Pros	Cons	Reference
Human health and hygiene	- SSF wetlands can treat domestic wastewater to a standard suitable for discharge into bodies of water and for reuse in various applications, e.g., irrigation and groundwater recharge, according to World Health Organization (WHO) guidelines. - SSF wetlands, if designed, operated, and maintained properly, can keep the liquid waste level completely below the vegetation bed surface; therefore, human contact can be avoided with this liquid waste during collection, transport, and treatment processes; no attraction is provided for insects that spread germs; and no inhabitants of nuisance species, e.g., mosquitoes. - SSF wetlands are reliable treatment equipment with high treatment efficiencies for pathogen removal; they remove up to 4-5 logs - CWs are accepted by public and communities because they - Are aesthetically pleasing equipment - add greenery landscape to a built-up area; - add no noise during operation - provide no offensive odour (because of aerobic treatment condition in the top layer of vegetation bed	- If liquid waste appears on surface of CWs due to clogging or operational and maintenance faults, human contact with this surface water should be avoided.	[Hof-11] [Til-14] [WHO-06] [Afi-13] [Bau-13] [Bri-07] [Gau-08] [Par-08] [Mas-07] [Lan-10] [Lan-12] [USEPA-02] [EAWAG-14] [Kro-16] [Poy-13] [Son-08] [Dav-95] [Rou-08]
Financial and economic	Small-scale CWs that can serve up to 500 *p.e.* require low operational and maintenance costs (i.e., low total lifetime cost) as compared to other conventional treatment equipment.	- Large-scale CWs that can serve more than 500 (*p.e.*) require greater capital costs. - CWs need more space compared to other conventional high-rate aerobic treatment equipment. - In urban areas, the high cost of lands pushes this alternative to the margins of sanitation markets. However, their accepted treatment efficiency, and low construction and operation costs have drawn attention to their use in urban areas across the world.	[Gaj-03]

Criteria	Pros	Cons	Reference
Environment and natural resources	- CWs have a high efficiency in removing organic matter, i.e., the BOD5 removal percentage can reach up to 98.9%. - CWs can treat liquid waste to a quality level that is suitable for reuse in agriculture and groundwater recharge based on Food and Agricultural Organization (FAO) - By harvesting the CW vegetation after some period, this vegetation can be a feeder to animals and can provide raw material for charcoal production. - SSF CWs produce no offensive odour and no air pollution during operation. - CWs have no contact and contamination to groundwater if properly lined.	- CWs treatment efficiencies may vary seasonally in response to changes in environmental conditions, e.g., rainfall and drought. Nevertheless, their average performance over the entire year may be acceptable. - Treated water by CWs cannot be reused if effluent quality does not meet stringent discharge standards at all times. - CWs can have better treatment efficiencies in warm climate areas, e.g., Mediterranean countries, as compared to those in cold climate areas, e.g. European countries. However, they can be designed to tolerate cold climates and periods of low biological activities. - CWs have high evapotranspiration rates in warm climate as compared to other extensive treatment equipment, e.g., stabilization ponds and sand filtration beds.	
Technology, operation, and maintenance	- CWs can be utilized for centralized and decentralized sanitation approaches and can be built in an individual household backyard if designed space is available. - CWs are low-tech equipment and they need low operational and maintenance requirements, i.e., nearly no electrical or mechanical equipment, and no chemicals for aeration, collection, and transport processes of liquid wastes treatment. - CWs can treat various types of wastewater (as specified in 1.3) - CWs do not require expensive vacuum pump trucks for desludging purposes. - CWs have high buffer capacity for hydraulic and organic load fluctuations as well as a high robustness and process stability. - CWs operation and maintenance are only periodic rather than continuous. - CWs are able to tolerate fluctuations in flow of the liquid waste. - CWs have the shortest hydraulic retention time (HRT) among the entire group of extensive treatment equipment, e.g., stabilization ponds and sand filtration beds.	- The influent liquid waste to CWs needs a pre-treatment to remove larger solids, e.g., toilet paper, rubbish materials, and bulk organic matter, to avoid clogging of pore spaces of the filtration media and to prevent appearance of surface water. - Overloading due to frequent clogging could reduce the CW treatment efficiencies and capabilities. - CWs require a long start-up time to reach their full capacity because their vegetation requires more time to grow in order to maintain the permeability of the vegetation bed and to improve the porosity of filtration media. - CWs require a minimum amount of water to survive. However, wetlands can bear temporary drawdowns, but they cannot tolerant a complete drying condition.	

3.4. Terra Preta sanitation

3.3.1. Overview of Terra Preta sanitation

Lack of improved sanitation and its negative consequences on human health and environment have persuaded researchers and scientists to develop efficient sanitation approaches that can address some of these fundamental concerns, particularly in emerging countries. The improved sanitation approaches also serve to alleviate the escalation in deterioration of soil quality in most areas worldwide. With respect to those urgent needs, Terra Preta sanitation (TPS) have recently been developed as a sanitation approach that is expected to play a key role in sustainable sanitation and resource-oriented sanitation [Fac-10], and as an alternative approach to the conventional approaches that often fail to maintain sustainability of both sanitation and agriculture. The main drivers of TPS include resource (waste) management, soil fertility enhancement, local energy production, and environment protection [Bul-13], [Gis-14].

TPS consists of a two-step process: lactic acid fermentation (LAF) process followed by vermi-composting (VC) process, as shown in Figure 3-4. Based on these processes, bio-solid wastes, e.g., food residuals, and blackwater solids can be converted into a hygienically safe and nutrient rich soil conditioner [Fac-10]. Findings on TPS from lab experiments at the Institute of Wastewater Management and Water Protection at the Hamburg University of Technology (TUHH) and from a field prototype in the house of Dr. Haiko Pieplow (Ministry of the Environment, Germany) have supported this hypothesis [Ott-09].

Application of TPS on the household level has proved to be simple, inexpensive, and culturally adopted, as well as the benefit of its implementation that does not pose health risks to the users [Fac-13]. TPS does not need water addition, air ventilation, or an energy source to work because it depends on natural processes, i.e., LAF and VC, to assimilate the bio-solid wastes with addition of charcoal to produce a nutrient-rich soil conditioner [Fac-10], [Gis-14].

TPS has been manifested to be an effective option for handling human excrement, controlling its offensive odour, and reducing its pathogen content in a short time period [Fac-13] compared to the storage time needed to render human faeces safe for reuse in farmlands, which ranges from 6–12 months [WHO-96], [Jön-04].

In TPS, producing a hygienic, safe, and nutrient-rich soil conditioner provides a valuable opportunity that allows plant nutrients, which have been consumed by humans in the form of fruits and vegetables, to return back to its origin—soil. This opportunity contributes to closing the loop on the nutrient cycle. Thus, TPS can significantly contribute to improving soil fertility and maintaining sustainability of agriculture [Fac-13], as well playing a key role in sustainable sanitation and resource-oriented sanitation [Fac-10], particularly in emerging countries, e.g., Ethiopia [Bul-13], Indonesia [Soe-13], Philippines [Fac-13], [Itc-13], and India [Pra-13].

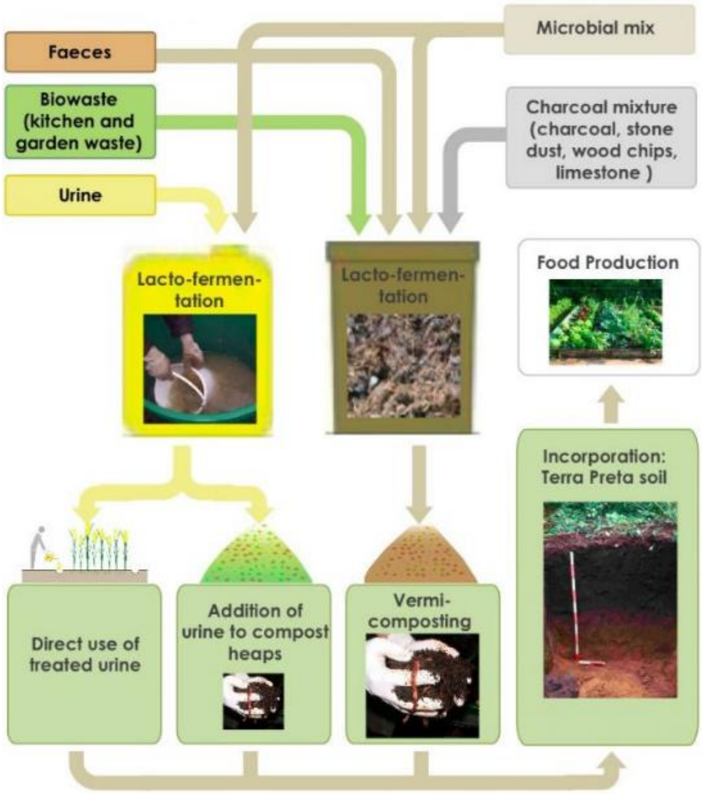


Figure 3-4: Concept of Terra Preta sanitation. Reprinted from [Spu-14]

3.3.2. Terra Preta soil

Terra Preta (TP) is literally "black soil" in Portuguese. It is also called “dark earth of the Indians”, “Terra Preta de Indio”, or “Amazonian Dark Earths” [Wds-04], as shown in Figure 3-5(a). It has been found in numerous sites within the Amazon-basin [Som-04].

Terra Preta was employed by ancient cultures through a cleaver integration of organic waste management by mixing together human and animal excrement, aquatic plants including algae, solid organic wastes, ash, bones from mammals and fish, and charred organic material, including charcoal and biochar [Gla-12], [Gla-13]. Hence, bio-solid wastes, including solid organic wastes and faecal materials, and charcoal are the main inputs for formation of TP soil [Wdr-14]. These soils contain high contents of organic carbon [Gla-00], which still exist in these soils since they were created several thousand years ago [Leh-06]. In addition to the high content of organic carbon, TP soils also contain high concentrations of nitrogen, potassium, and phosphorus, which could be derived from various sources, primarily from solid organic waste and human excrement [Bet-13]. The organic matter and nutrient content that exists in TP soils is three time greater than that existing in surrounding normal soil [Gla-07], Figure 3-5(b). Approximately 250 tonnes of organic carbon also can be found in one hectare of metre-deep TP soil, while about 100 tonnes are found in infertile soil [Leh-06]. This makes the TP soil potential for crop production two times greater than that of surrounding normal soil [Gla-07].

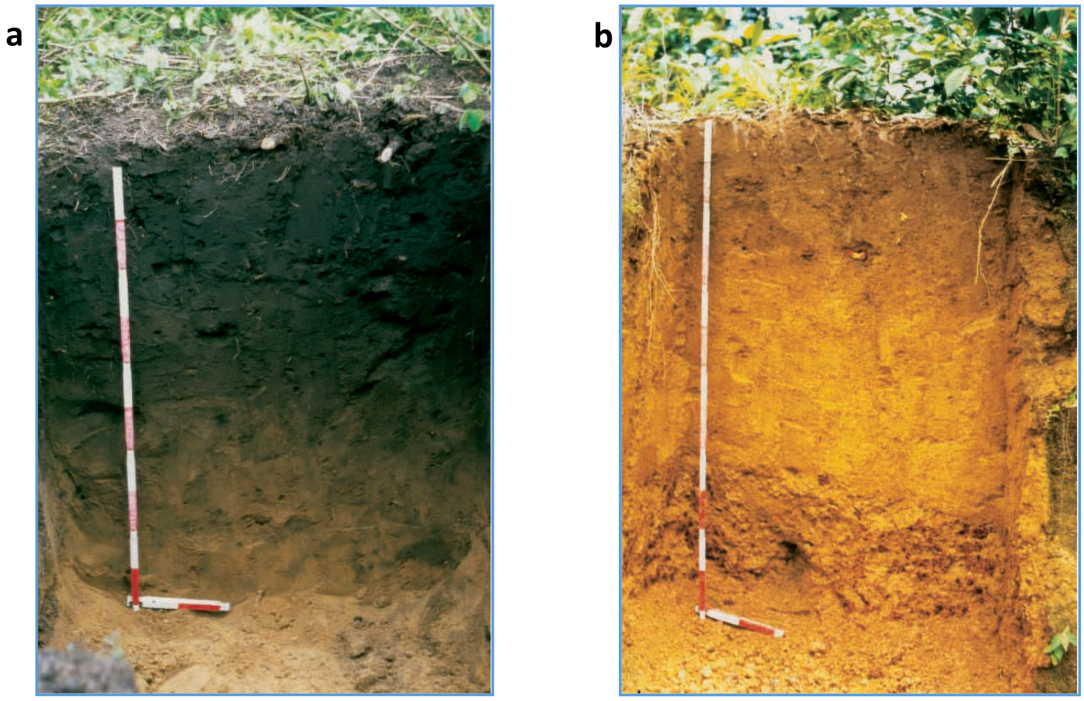


Figure 3-5: (a) Typical profile of Terra Preta soil; (b) typical profile of normal soil. Reprinted from: [Gla-01]

Although there is a consensus about the original formation of TP soils due to man-made activities of pre-Columbians indigenous people of the Amazon-basin, it has not yet been established whether the TP soil was obtained by intentional activities for improving soil fertility, or as a consequences of agricultural and domestic activities of these people [Nov-09].

3.3.3. Importance of charcoal addition

In line with the scope of this thesis, the term, charcoal, is used to describe the carbon-rich material used either for soil amendment or wastewater treatment, keeping in mind the strong relation between charcoal and biochar in their key properties.

Charcoal is a good carbon source with a long-term carbon storage capacity and is a very slow biologically degradable material [Sjy-10]. Its involvement in the chain of treatment of faecal material with soil amendment has several benefits, including improvement of soil fertility and enhancement of long-term crop production [Bet-13].

The amount of charcoal in TP soil is 70 times greater than that in the surrounding normal soil [Gla-01]. This evidence indicates that charcoal is a key ingredient that forms the special characteristics of TP soils, which contain only approximately 20% charcoal [Gla-13] or approximately 35% charcoal and black carbon combined for its soil organic matter [Gla-00]. Nevertheless, any trial to copy TP soil should focus on combining charcoal with other materials that are rich in nutrients and organic matter [Slz-12], e.g., human excrement.

Charcoal is characterised by its high stability, which makes it an interesting compound for carbon sequestration and gives it a high capacity for nutrient holding in soil. Moreover, its high porosity enhances air and water storage in soil. Addition of charcoal to either compost or chemical fertilizer has a significant effect on plant growth and plant biomass, which have increased by factors higher than that of pure charcoal, pure compost, and pure chemical fertilizer. Specifically, the response of a mixture of charcoal and compost was significant on plant growth and soil quality, e.g., cation exchange capacity, and nutrient contents and availability. Therefore, the combination of charcoal with compost "organic fertilizer" is most promising option for agricultural activities[Slz-12]. Moreover, this combination has increased the retention of nitrogen in the soil more than that when only chemical fertilizer is used. This leads to a conclusion that addition of charcoal is responsible for the higher nitrogen retention in the soil and the increased plant uptake of nitrogen [Stn-08], and reduction in nitrogen leaching from the soil [Leh-03].

Biochar is another product that differs from charcoal in its manufacturing but that has similar key characteristics to charcoal [Soh-09]. Biochar is a carbon-rich product obtained by heating or thermal decomposition of organic matter, e.g., wood, leaves, or manure, in limited oxygen or the absence of oxygen, and at relatively low temperatures below 700°C [Leh-09]. This process is also known as pyrolysis. One of the significant aims of biochar applications involves the addition to soil for improving its fertility through increasing of (i) soil organic matter, (ii) plant nutrients, (iii) microbial activities, and (vi) water holding capacity, and reduction of (i) needs for chemical fertilizers and (ii) leaching of nutrients and soil erosion. [Soh-09].

Addition of biochar to farmland soil is also compatible with sustainable agriculture practices, particularly when mixed with nutrient-rich wastes, e.g., slurries and organic blackwater solids [Gla-07], [Gla-13]. This can help in regeneration of TP soil that has a potential to maintain sustainable agriculture with long-term carbon sequestration [Gla-02], [Gla-12] to reduce greenhouse gas emission, e.g., CH_4 and N_2O [Spo-09], [Sjy-10]; hence, biochar can participate in the mitigation of climate change [Soh-09].

Although a large number of studies have revealed the significant benefits of biochar on soil and the environment, a few studies have shown that biochar has no appreciable effect on soil [Soh-09], [Slz-12]. The effect of biochar on soil and the environment has been the subject of various research studies [Lia-06], [Leh-06], [Leh-09], [Lai-10], [Lai-10] ,[Leh-11], [Kam-11], [Slz-12].

From another point of view, biochar has been significantly applied for treatment of groundwater, surface water, domestic and municipal wastewater, and industrial wastewater [Mhn-14]. A research study by [Hin-13] has revealed that pine biochar that is produced from woodchips at 550°C has a low capacity to recover nitrogen and phosphorus from wastewater. Moreover, a pine biochar that is activated by alkaline treatment has significantly increased the ammonia nitrogen adsorption compared to one activated by steam that has increased the surface area of biochar but not its adsorption capacity [Hin-13]. However, further chemical treatment performed on the biochar to improve its adsorption capacity would increase its production costs, depending on the type of feedstock and its moisture content [Lai-10].

The capacity of adsorbent materials, e.g., zeolite and charcoal, to remove nutrients from wastewater, is dependent on (i) type of wastewater, (ii) hydraulic and organic loading rates, and (iii) contact time between adsorbent particles and wastewater [Ngu-10]. In addition, (vi) alkalinity (pH) of wastewater and (v) temperature of wastewater were further factors [Maz-16].

3.3.4. Implantation and processes

TPS has been developed on the basis of coupling the LAF process with the VC process [Fac-10] as follows:

Lactic acid fermentation process

The LAF process is also called the lacto fermentation process. It is similar to that of silage production in agriculture, which works under anaerobic conditions but with no biogas formation for initial stabilization of the bio-solid wastes. For many years, the LAF process has been practiced to convert food residuals into livestock feeds, produce fish silage, control offensive odour of bio-solid wastes, and reduce pathogen content [Fac-10].

The LAF process is well-known and is mainly used either to produce food, including milk fermentation products, e.g., traditional butter and buttermilk [Bul-13], or to preserve food, i.e., vegetables and fruits, e.g., pickles and pickled cabbage, or sauerkraut [Ott-09], [Fac-10]. LAF process for effectively stabilizing of organic backwater solids requires addition of a microbial mixture, which can be produced from various fermentation products that are previously fermented and can be locally available, e.g., pickled cabbage, or sauerkraut [Bul-13]. The microbial mixture is termed effective microorganisms (EM) and consists of a mixture of five microbes: *Lactobacillus sp., Azotobacter croococcum, Bacillus subtilis*, *Bacillus mesentericus*, and *Geobacillus stearothermophilus* [Spu-14].

The LAF process also can be performed on organic backwater solids, either fresh faeces or faecal sludge [Fac-13]. The LAF basic condition can be achieved simply by storing the solids in a specific container [Soe-13]. Although the offensive odour production is a common problem in the treatment of backwater solids, the LAF process has the advantage of removing the offensive odour [Soe-13] because it does not need air exchange for stabilizing the organic matter and thus it does not produce an offensive odour [Fac-10], [Sut-14]. This advantage makes it particularly interesting for in-house use [Gis-14].

The key indicator for the successful LAF process is the production of lactic acid [Joh-07], which is produced in high amounts by the lactic acid bacteria [Soe-13]. Another strong indicator for LAF is the vinegar-like odour, which was noticed when a microbial mixture was added to the UDDT toilets. No such vinegar-like odour was experienced by the users who did not use the microbial mixture [Fac-13].

The LAF process has an advantage of reducing the pathogen content, as it has been noticed that faecal pathogen indicators, e.g., *E. coli*, *Shigella Dysenteria*, and *Salmonella,* were drastically reduced during LAF of poultry manures [Jal-08]. Other faecal pathogen indicators were reduced in fresh human faces to safe limits; e.g., *Total Coliforms* [Soe-13] and *Ascaris Eggs.* [Fac-13] and [Itc-13] noticed that *Ascaris Eggs* were reduced by 50% after 30 days and 100% after 60 days when a microbial mixture was also added.

Another study on the performance of LAF process for faecal sludge obtained from six small wastewater treatment facilities in the area of AZV Leisnig, Germany, has revealed that *Salmonella* and other gram-negative bacteria were successfully disinfected. Based on results of faecal sludge samples that were analysed in the Faculty of Veterinary Medicine, Mycology at Leipzig University and Institute of Bacteriology, enterococci bacteria that can endure up to 7 days in the fermented mixture has been eliminated, and its concentration was below the detection limit of 3 $\log_{10}$ " colony forming unit" Cfu/g.[Böt-13]. This could be due to the production of a bacitracin-like substance [Moh-10] or the production of lactic acid, which causes a rapid drop in alkalinity to about pH 4, which is not a suitable environment for a wide range of microorganisms [Fac-13]. The disinfection of faecal sludge that is produced from small wastewater treatment facilities by means of the LAF process complies with the standards of the German Fertiliser Ordinance (DüMV) [Böt-13]. Therefore, using the LAF process in the TPS can facilitate the hygienisation of faecal materials in a safe and inexpensive manner [Sut-14].

The LAF process has a positive effect on the organic matter and plant nutrients [Wag-13]: total nitrogen (TN) was slightly increased by 17–39% from initial values, while ammonia (NH_4^+) increased by approximately 190–280% [Pra-13]. The response of the plant to the LAF process for composted material, including plant residuals, e.g., leaves and grass, with the addition of charcoal and the microbial mixture, was a 23% increment in plant height. The plant height was only increased by 15% when the composting process, alone, was carried out in the Botanic Garden, Berlin, Germany, although no major difference was found in the response of the plant. The increase in plant height was determined to be related to the availability of nutrients that can be improved by addition of charcoal [Wag-13]. This conclusion is also compatible with other studies [Stn-07], [Slz-12]. Therefore, the LAF process does not prevent decomposition of organic matter. However, it can avoid emission of greenhouse gases before the starting composting process for bio-solid wastes. LAF can also prolong this decomposition process; hence, a longer crop production process can be achieved [Wag-13].

Vermi-composting process

Vermi-composting, also called vermiculture, is the practice of cultivating earthworms, e.g., *Eisenia fetida*, while converting bio-solids wastes, e.g., food residuals, agriculture wastes, blackwater solids, and faecal sludge, into soil conditioner products [Eas-01]. In other words, VC is an aerobic decomposition process of bio-solid wastes by the combined effect of both earthworms and microorganisms [Fac-10, p. 2674], [Fac-10] which does not involve a thermal stage [Yad-10, p. 50]. VC product (vermi-compost) has a fine particulate structure and contains nutrients that are available for plant uptake. VC products have encouraging characteristics, e.g., high porosity and water-holding capacity, which have contributed to several authors describing it as a humus-like substrate that can be used as a soil conditioner or organic fertilizer for various types of crops [Ati-00]. An exhaustive review of vermicomposting and its theory, process, implementation mechanisms, and practical applications were addressed by [Sha-06] and [Buz-10].

VC is a new concept in the field of sustainable sanitation [Fac-10], and it is a crucial step for production of a Terra Preta-like substrate [Fac-10], [Pra-13], [Pra-15]. VC can be one of the most appropriate alternative to conventional aerobic composting, because it is not only easily controllable, cost effective, energy saving, rapid, and produces zero waste, but it also accomplishes the efficient recovery of nutrients and recycling of organic matters [Eas-01, p. 38 ff.]. Alone, VC has been proven to be highly efficient for treatment of faecal materials [Sha-06], [Yad-10] for producing beneficial soil conditioner products [Eas-01].

The VC process consists of five key stages, including preparation of bio-solid wastes, provision of composting chamber or compartment, harvesting and separation of earthworms, processing of earthworm by washing and soaking in water, and processing of composting [Gry-04]. VC is easy to manage with very minimal hands-on effort for operation and maintenance, and it can be done on the household level with an affordable capital cost to poor people [Fac-13]. Moreover, the earthworm can be made available for commercial purposes with little additional processing [Eas-01].

Based on a field study conducted on VC of faecal material that was produced at a public toilet at Hamburg central station, Hamburg, Germany, a well-stabilized soil conditioner can be produced within less than three months. The faecal materials were mixed with other substances including charcoal, grass cuttings, sliced wood, fruits, and vegetables, and stored in airtight containers for another three months to perform the LAF process [Bet-13].

A preliminary pilot study was conducted by the Orange County Environmental Protection Division, in partnership with the American Earthworm Company, Florida in 1996 at the City of Ocoee's Wastewater Treatment Facility in Ocoee, Florida to investigate the effectiveness of earthworms on removal of faecal pathogens. The study demonstrated a noticeable reduction in four faecal pathogen indicators, including *faecal coliforms, Salmonella spp., enteric viruses,* and *helminth ova* in the faecal materials [Eas-01].

A field experiment determined the feasibility of the VC process with the help of earthworms, *Eisenia fetida,* as a method for eliminating faecal pathogens to obtain United States Environmental Protection Agency (USEPA) Class A bio-solid wastes, i.e., faecal sludge, stabilization. The test indicated a significant reduction in four faecal pathogen indicators: *faecal coliforms, Salmonella spp., enteric viruses* and *helminth ova* by 6.4 log, 8.6 log, 4.6 log, and 1.9 log, respectively [Eas-01]. [Fac-10] have monitored a significant reduction in six faecal pathogen indicators, namely *Escherichia coli, Faecal coliforms, Enterococcus faecalis, Salmonella spp., Shigella spp.,* and *Enterobacter spp.* in the faecal material that underwent LAF for 30 days, followed by VC for 60 days. Results have also revealed that participation of earthworms in the VC process caused greater reduction in the monitored pathogens [Fac-10]. A 3–4 log reduction in indicator pathogens would be sufficient to ensure the successfulness of the VC process as an effective stabilization method, as established by Dr Jim Smith, Senior Environmental Engineer and Pathogen Equivalency Commission (PEC) Chair, for the USEPA [Eas-01]. The VC process can be used as an alternative option for removing faecal pathogens that are contained in human excrement [Eas-01], [Fac-10].

However, other studies have criticized the capability of the VC process for not providing enough hygienisation and eliminating the faecal pathogen indicators. A field experiment that used a combination of the LAF and VC process was conducted to test the effectiveness of the VC process for eliminating the faecal pathogen indicator, *Ascaris ova,* in fresh human faeces in UDDT toilets in Cagayan de Oro City, Philippines. Results revealed that *Ascaris ova* was completely eliminated from the sample of the soil conditioner, which was produced by the VC process, when a microbial mixture was added to the human faeces. In addition, *Ascaris ova* still was noticed in the faeces sample after 30 days of LAF and VC processing without the addition of the microbial mixture [Fac-13]. Another study showed that the VC process with the involvement of earthworms, e.g., *Eisenia fetida,* was not able to eliminate *Salmonella* from the mixture of faecal materials, charcoal, and other organic solid waste, e.g., food residues and plant cuttings. Results revealed that temperature is the key factor in the hygienisation process for the faecal material because *Salmonella* was not noticed in the composting heaps that reached a maximum temperature of 58.4°C [Sto-13]. This result was compatible with the requirement of hygienisation in the aerobic treatment, e.g., VC and normal composting, of faecal material, which stated that the temperature of such material should be at least 55°C over a period of two weeks, 60°C over six days, or 65°C over three days [BioAbfV-98].

Conversely, the VC products had a better effect on growth of plants and yield of higher nutrient concentration of N, P, and K compared to the other composts, as found by [Kar-99] while comparing the VC product obtained from decomposed pods of the green gram, *Phaseolus aureu,* using the earthworm, *Eudrilus eugeniae*. A better germination of *Phaseolus aureu* (93.3%) was achieved, compared to 84.2% germination by normal compost [Kar-99]. Moreover, VC product obtained from cattle manure has been used to remove heavy metals, including Copper (Cu), Chromium (Cr), Nickle (Ni), Zinc (Zn), and Cadmium (Cd), from electroplating industrial wastewater. The treated effluents were below the maximum values that are allowed for waste discharges into bodies of waterbodies of water, i.e., rivers, by the Brazilian Environmental Standards [Jor-02]. VC has the advantage of being not only an odour-free process, but also its product (vermicompost) can be used to remove offensive odour produced from other treatment processes or from livestock rearing locations [Gry-04].

VC is a preferred process to normal composting for the following reasons:

1- No additional effort in terms of mixing or re-piling is required once the compost heap is prepared and the earthworms are introduced [Bet-13, p. 6].
2- VC is more suitable and easier to realize as a safe treatment method for faecal material than typical composting without worms [Sha-06].
3- During VC, lower temperature is developed compared to thermal composting. This assumes that nitrogen emissions are significantly low and nutrient recovery is efficient, although relatively high temperature was noted within the first three days of the VC process [Bet-13, p. 6].

4. Requirements for resource-oriented sanitation in emerging countries

At the beginning of the 21st century, many parts of the world, particularly the emerging countries, face a severe sanitation crisis, leaving 2.4 billion people without access to improved sanitation [WHO-15]. Global water scarcity and quality deterioration is another problem, as 50% of world population is expected to live in water-stressed areas by 2025, and at least 1.8 billion people will be estimated to have access to a source of drinking water contaminated by faecal materials [WHO-16].

Worldwide, wastewater management will be presented with a challenging situation, resulting in disposal of more than 90% of wastewater into bodies of water and the environment without receiving any kind of treatment [UN-CSD-97], [Crc-10]. This will cause a spread of faecal-borne diseases that will pose health problems and pollute a large amount of fresh water by an eutrophication phenomenon that will seriously harm the aquatic life [UN-Water-15].

Although conventional centralized management of wastewater has made a revolution in protecting human health, it is not an economic option for poor communities in emerging countries [Par-03]. Its success requires high investment costs [Kro-16] that are connected to the complex infrastructure of household connections, water-borne sewers, electrical pumps, and WWTPs. The WWTP, itself, requires significant amounts of resources, e.g., electricity and chemicals, as well as skilled labour for operation and maintenance. Because the conventional centralized sanitation is a water-based approach, high water consumption is a big challenge, particularly in water-stressed areas. Additionally, the design of the conventional centralized approach is based on at-source mixing of all wastewater streams, which makes the nutrient recovery to produce a fertilizer complicated and the reuse of greywater uneconomic [Ott-02]. This means, unfortunately, that drinking water, nutrients, and potential energy are wasted [Ng-12, p. 83]; approximately 70% of nitrogen is lost in this approach [Kau-07]. Consequently, the conventional centralized approach may not contribute to economic and environmental sustainability.

Yet, with increasing population growth, the conventional decentralized approach—drop and store—is not an appropriate solution for the sanitation crisis, particularly in densely populated areas. It is not often capable of protecting the environment and in avoiding contamination of groundwater [Wer-03, p. 4], although it releases pressure on drinking water sources and has been listed in the group of improved sanitation facilities [WHO-15].

Furthermore, bad design and improper management of decentralized sanitation facilities, e.g., pit latrines, allow untreated faecal materials to be dumped into the environment, as well as untreated liquid waste to infiltrate into soil, carrying all soluble elements and pathogenic organisms [Wer-03].

Although the MDG target on sanitation has focused on increasing coverage in terms of access to improved sanitation facilities, less attention has been paid toward adequate management of wastewater collection. Effective reuse of wastewater can yield multiple benefits for future water and food security. Presently, only 7% of crop lands are irrigated by wastewater in emerging countries [WHO-16]. Therefore, a paradigm shift in water and sanitation management is essential now, not only for preventing further health risks and deterioration of the environment, but also for emphasizing wastewater as a valuable resource for water, nutrients, and energy [Mei-10]. Sustainability depends not on wasting these resource, even if they are safely disposed or dumped, but on how to recover these resources [Gue-09, p. 6127]. This shift can be carried out based on a resource-oriented approach that integrates both water and agriculture and operates across all three dimensions of sustainable development: social, economic, and environmental.

The decentralized and resource-oriented approach recently has been given more attention due to its potentials not only to reduce high water consumption, but also to reduce environmental problems [Bha-01, p. 322 ff.], [Wil-16]. In addition, it has the potential for recovering valuable nutrients and easy linking them to agriculture [Ott-02], [Ott-03].

The basic requirements to make the decentralized approach for human excrement and wastewater management become competitive and effective are as follows:

- Human excrement and wastewater should be treated at a location close to where they are produced and to where their reuse potentials are located [Bha-01].
- Human excrement and wastewater should be treated, using low-cost, effective, robust, and easy-to-operate processes and equipment, and by an effective participation of humans who are willing to operate and maintain such tasks [Wil-00].
- A regular monitoring and inspection program should be incorporated to manage treatment processes and equipment effectively [Mss-09].

The decentralized and resource-oriented approach includes modules that can meet stringent limitations to wastewater effluent, which are made to release pressure on human health and the environment. Development of innovative and more economical modules are needed for a widespread acceptance, specifically in emerging countries. However, improving the reliability and predictability of these modules as well as their performances requires technological innovations, but also in-depth knowledge on the treatment processes involved and how they interact [Bri-07]. Therefore, such development requires extensive research and prototype realization using both simple and sophisticated processes and equipment.

The major requirements of such innovative modules, includes:

- Effective and efficient in removing pathogenic organisms and preventing direct contact between human and excrement.
- Effective and efficient in recovering water and nutrients of wastewater and making them available for use in agriculture.
- Low-cost and affordable to poor people.
- User friendly and does not causing nuisance to community.
- Less space requirements for implementation and realization.

From another point of view, depletion of soil fertility in many parts of the world is a major concern [Bet-13], as it greatly undermines the sustainability of crop production and food security. Hence, the ability of agriculture to meet escalating demands of the growing world population that reached 7.3 billion in 2015 and is expected to exceed 8.5 billion by year 2030 [UN-15] is questionable in the near future.

Soil degradation is primarily caused by reduction in the content of plant nutrients that flow in a one-way path from farmlands to bodies of water in the conventional linear sanitation approaches, mainly “flush and discharge”, and “drop and store” [Win-04]. This linear flow results in high demands on industrial chemical fertilizers to compensate for the reduction in plant nutrients. Although industrial fertilizers are effective to cope with soil degradation, they cannot be a reliable and sustainable solution as they depend significantly on non-renewable resources and high energy. A key ingredient of industrial fertilizers is phosphorus, which is a very limited element on our planet, and its production through mining and refining of raw materials produces hazardous wastes to health and the environment. Production of industrial fertilizer through nitrogen reduction into ammonia is costly and depends on non-renewable resources, oil and natural gas [Gre-98], which are expected to reach their global peaks in 10 or so years [Ben-02], for oil in year 2015 and for gas in year 2035 [Mag-12].

Through the conventional sanitation approach, plant nutrients are permanently removed from the food chain. The big challenge is to close the loop on the nutrient cycle [Roc-15].

Therefore, a paradigm shift for closing the nutrient loop is an imperative need to promote sustainable agriculture. One possible option for this shift is a linkage between agriculture and resource-oriented sanitation. This linkage allows plant nutrients to return back to the soil again in a more effective and sustainable way, instead of depending on industrial fertilizers.

5. **Concept of resource-oriented sustainable sanitation module**

5.1. Basic concept

The concept of the resource-oriented sustainable sanitation ROSS module, which is introduced in this thesis, has basically emerged from the "resource-oriented sanitation approach, ROSA" [SuSanA-08], which considers human excrement as a valuable resource rather than a waste. The ROSS module aims to meet sanitation needs by fulfilment of the hygiene requirements during on-site handling of human wastes, including domestic wastewater and solid organic waste, e.g., food residuals, and reusing of recovered nutrients. The module tries to close loops on water and nutrients by interlinking sanitation with agriculture through the use of locally available materials with as few energy requirements as possible. The decentralized module selects some technological components from the wide pool of available components. These components are characterised by low technology; low cost; ease of implementation, operation, and maintenance; applicability for a single household or a group of households; and ability to be culturally adoptable for communities in semi urban and rural areas in emerging countries.

The decentralized module integrates both concepts of TPS and CWs, as shown in Figure 5-1, to handle and manage the bio-solid wastes and liquid wastes at a household level to use their benefits in maintaining a sustainable and resource-oriented sanitation and agriculture.

The ROSS module is applied where conventional decentralized sanitation facilities, e.g., water flushing toilets and septic tanks, are used. Based on the workability of TPS and CWs, the decentralized module depends on natural processes, e.g., infiltration of liquid, adsorption of nutrients, aerobic biodegradation of pollutants, and fermentation and aerobic decomposition for bio-solid wastes.

The basic concepts that helped in the development of ROSS module are summarized as follows:

- At-source separation and collection of blackwater, greywater, and solid organic wastes, e.g., food residuals, to simplify the handling and treatment of each portion and to facilitate the recovery and reuse of valuable resources of water and nutrients.

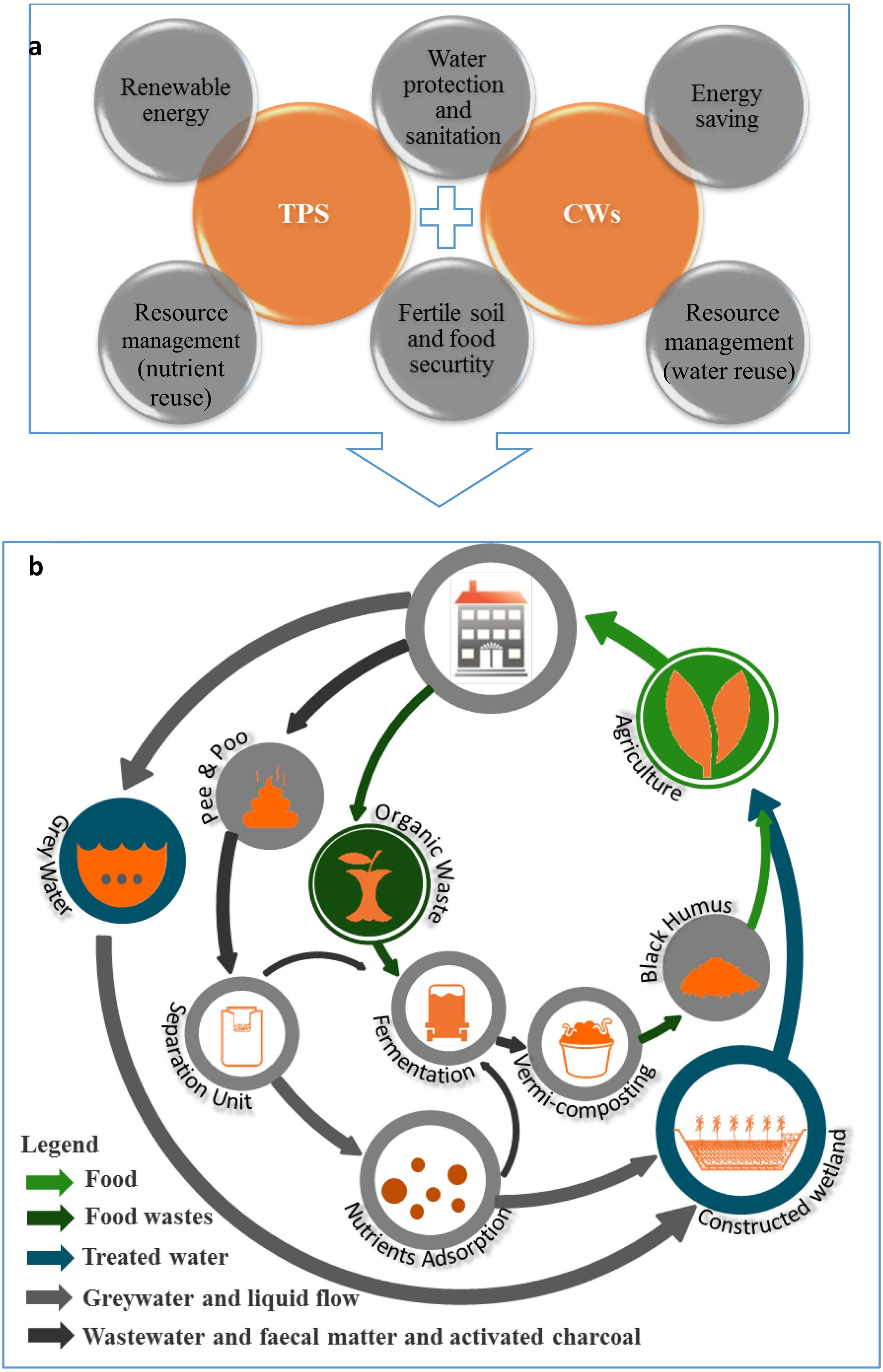


Figure 5-1: Concept of resource-oriented sustainable sanitation (ROSS) module; (a) adopted from [Hof-11] and [Gis-14], (b) designed by Alnahhal, Samir, 2017.

- Separation of faecal materials, i.e., blackwater solids, from liquid waste of blackwater using solid-liquid separation equipment that is designed and developed in this thesis. Separation of faecal materials from liquid waste has double benefits: first, reducing the organic load of liquid prior to treatment via CWs to reduce its required areas [Hof-11]. Second, lowering the water content of faecal materials for better and faster treatment and recovery of nutrients via lactic acid fermentation and aerobic decomposition for production of Terra Preta-like substrate [Fac-10].
- Adsorption of nutrients contained in the liquid waste of blackwater by using charcoal as a locally available and natural material aims to activate charcoal and to reduce nutrient losses in that liquid before entering the constructed wetland. The activated charcoal can be used as nutrient-rich material with the bio-solid wastes for production of Terra Preta-like substrate that can be used for fertilizing the soil.
- Treatment of liquid waste blackwater and greywater via constructed wetland to produce hygienically safe treated effluent that can be used for irrigating plants.
- Development of a decentralized sanitation module depending on locally available materials and recyclables with less use of energy.
- Although this module is context-specific to the environment in the Gaza Strip, it can be applied in other areas, worldwide, where environments have similar conditions to that of the Gaza Strip.
- Design, development, realization, and monitoring of a decentralized prototype of the ROSS module and disseminating of findings to the scientific community.

5.2. Linkage to agriculture

In view of the rising needs to close loops on the nutrient cycle and improve soil fertility, the ROSS module considers this imperative need by linking the sanitation module to agriculture. This linkage is achieved through the following steps:

- Reduction of the water volume of wastewater in which the plant nutrients are diluted and by which their recovery becomes difficult. In the ROSS module, the separation between the main wastewater streams, i.e., blackwater and greywater, is achieved in the containment process by using additional pipes for each stream. A large amount of water in the greywater is prevented from mixing with the blackwater. Moreover, managing the blackwater solids becomes more effective and easier compared to the entire volume of wastewater. Lesser water content of human excrement means a more favourable condition for hygienisation and production of soil conditioner [Gaj-03].

- Recovery and storage of plant nutrients contained in blackwater solids via a solid-liquid separation equipment which separates blackwater solids from liquid and stores them in a safe and hygienic manner until a favourable time for treatment. Moreover, this separation can be achieved either at-source in the toilets or at the collection, storage, and on-site treatment process [Bet-15].
- Recovery of plant nutrients contained in blackwater liquid via nutrient adsorption tank, where charcoal is used as a natural adsorbent.
- Recycling of plant nutrients by treating and hygienisation of a mixture of blackwater solids and charcoal via lactic acid fermentation, thermal composting, and aerobic composting, and production of nutrient-rich soil conditioner that can be reused for fertilizing farmland soil.

5.3. Service chain

In general, sanitation is considered as a multi-step process. The "cradle to grave" principle describes the life cycle of human wastes in the conventional approaches, where "cradle" is the point of generation at the households, while "grave" is the last point of destination at the receiving environment. In between the "cradle to grave", a multi-step process occurs, including storage, collection, transport, and treatment [SuSanA-08]. This process, also called the sanitation service chain, consists of containment, collection, and on-site treatment, transport, (semi-) centralized treatment, and safe disposal and reuse. A lack of consideration of all components of the sanitation service chain causes many problems, particularly in urban and semi-urban areas. Therefore, all facilities along the service chain should be managed effectively for better performance and functionality of the sanitation module as a whole [Par-14, p. 28], [UN-Water-15, p. 14].

In the conventional centralized sanitation approach, which is water- based, the containment process is the starting point in the service chain. At the household level, it is performed by water flushing toilets, urinals, washbasins, and showers where human excrement and wastewater are kept away from human contact [Vli-10, p. 2]. The collection process is performed by the means of household connections or pipelines. Similar to the conventional on-site approach of water-based sanitation, the human excrement and wastewater could be partially treated on-site via septic tanks or Imhoff tanks before being removed to the next transport process. But most often, there is no on-site treatment as no septic tanks are constructed. The transport process is performed by water-borne sewers and electrical lifting pumps for washing and transferring these wastes from their production location to the place of the treatment where the (semi-) or centralized treatment is carried out by WWTPs [UN-Water-15, p. 14]. Eventually, the treated water effluents and treatment products, e.g., faecal sludge are sent either for disposal in the nearby bodies of water or dumped in landfills, respectively, or for reuse in agriculture. In the conventional on-site approach of dry sanitation, the service chain has no transport and centralized treatment processes.

In line with the ROSS module, the segments of the sanitation service chain are performed for a household that already uses water-based sanitation, but has not been served by any transport or central treatment process, as shown in Figure 5-2. The ROSS service chain is described in the following sections.

5.3.1. Containment process

Domestic wastewater primarily consists of blackwater and greywater, which are considered as output products for the containment process. The blackwater source is household toilets and consists of faeces, urine, toilet paper, anal cleansing water, and toilet flushing water, while greywater source is kitchen taps, washbasins, laundries, and showers. These wastes are deemed as input products in the containment process. In most new buildings in urban and semi-urban areas, blackwater and greywater are separately collected from the house via household connections before being mixed in one pipe outside the house. Therefore, their separation can be simply achieved compared to old buildings that mix both streams inside the house.

The solid organic wastes, e.g., food residuals, can be at-source separated from other solid non-organic wastes and recyclables at a household level. These organic wastes as input/output products of the containment process can be collected in separate recycling bins. Similarly, the garden wastes can be collected for further treatment and production of soil conditioner or compost. Garden waste is also an input/output product of the containment process.

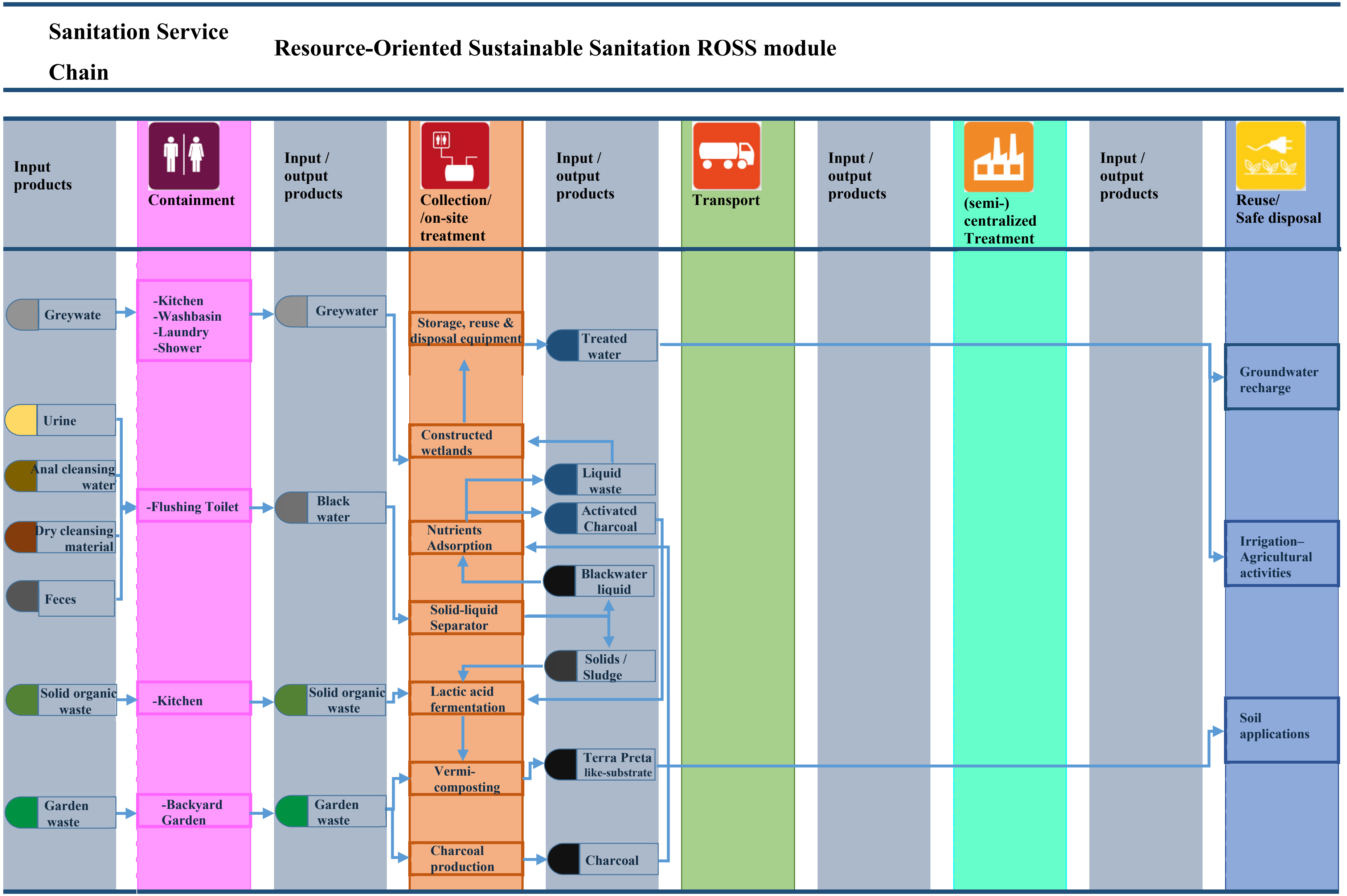


Figure 5-2: Flow scheme of ROSS approach.

5.3.2. Collection, storage, and on-site treatment process

The blackwater stream as a containment output product is an input product for collection, storage, and the on-site treatment process. The blackwater stream is collected via the use of separate pipes. Then, it passes under gravity toward the solid-liquid separation equipment, where the blackwater solids are separated and stored inside prior to removal for further treatment by lactic acid fermentation and aerobic composting. Meanwhile, the blackwater liquid flows toward the nutrient adsorption tank where charcoal is added for adsorption of nutrients. Then, blackwater liquid passes to the subsurface flow wetland for further purification and treatment. The nutrient- and carbon-rich charcoal can be mixed with the blackwater solids for production of a Terra Preta-like substrate, which is an output product of collection, storage, and the on-site treatment.

The greywater stream as a containment output product is an input product for collection, storage, and the on-site treatment process. The greywater stream is also collected in separate pipes. It flows directly toward the SSF wetland and joins the blackwater liquid for purification purposes prior to reuse in irrigation. Further purification can be achieved via using ultraviolet (UV) radiation equipment. The treated effluent from the SSF wetlands is an output product from collection, storage, and on-site treatment.

The solid organic wastes and garden wastes as output products of the containment process are input products for the collection, storage, and on-site treatment. These wastes can be mixed with the faecal solids and charcoal for decomposition and greater hygienisation [Ott-02, p. 153] through the composting process.

5.3.3. Reuse and safe disposal process

Treated water as an output product of the on-site treatment process is an input product of the reuse and safe disposal process, where this water can be reused in irrigation. However, its quality must be checked before reuse by performing laboratory sample testing for its physical, chemical, and biological properties that should comply with the reuse standards provided by the WHO [WHO-06]. Similarly, the produced Terra Preta-like substrate as an output product from the on-site treatment process is an input product for the reuse and safe disposal process. This substrate can be used in gardening for increasing soil fertility and enhancing the water holding capacity. However, its physical, chemical, and biological properties must comply with the reuse standards provided by the food and agricultural organization, FAO [Pes-92].

5.4. Technological components for sustainable sanitation modules

In sanitation, to be comprehensive and realistic in finding a suitable introduction for a more sustainable approach in a specific area, one needs to determine what works and what does not by putting into practice and prototyping. This practice facilitates gathering relevant information and accelerates the education and communication of this innovative solution. Then, further adaptation and upgrading can be done [SuSanA-08, p. 10].

Predicting the performance of sanitation modules, which depends on the nature for wastewater treatment, e.g., constructed wetlands and composting, requires an understanding of the relationship between the environment and the operating conditions. Hence, improving the reliability and predictability of the modules as well as their performances needs technological innovations, but also in-depth knowledge of the treatment processes involved and how they interact [Bri-07]. The sanitation service chain for such modules may comprise several technological components, including processes and equipment, e.g., septic tanks, pit latrines, and composting toilets, which can be combined and designed according to the prevailing conditions in a particular area or for a certain community [Bha-01, p. 322 f.].

Currently, many technological components in sanitation are available and could form a sustainable approach, if designed properly and linked with other components [Gue-09, p. 6127]. Most often, some components are implemented and other essential ones are missing, e.g., those components needed for efficient treatment and reuse of wastewater, causing wastewater disposal to the environment without treatment. As a result, a technological component may work well, but the entire sanitation approach might be unsustainable [SuSanA-08, p. 6].

Recent innovative research and development (R&D) projects for resource recovery from wastewater have proven feasible for application in urban areas, although the suitability of all current technological components for making a sanitation approach sustainable has not been examined yet [Kat-12]. However, the problem is in the lack of adequate planning and design methodologies for selecting the most sustainable solutions that fit with local conditions and public cultures of a certain area [Gue-09, p. 6127]. Moreover, replication of successful projects without making appropriate adjustments to the local conditions would lead to a big failure [Mss-09, p. 658]. Therefore, choosing between expansion of current approaches while keeping their drawbacks or searching for new sustainable approaches is challenging, not only for the involved stakeholders but also the entire communities [Esr-98, p. 9]. However, seeking adequate and sustainable solutions should not stop, and preparing comprehensive and long-term strategies for proper planning and implementation of sustainable sanitation is essential [Mss-09, p. 658].

Generally, the development and implementation of sustainable approaches relies on three pillars:

1) Creation of local demand by creating ownership, i.e., sanitation provision, is a demand-oriented service, and no special option should be forced to the users.
2) Establishing appropriate local supply of resources, equipment, and labour by developing active supply chains for goods and services.
3) Enabling the working environment, e.g., polices, strategies, regulations, and legislations, by governments and involved stakeholders. However, it is most often the case that sanitation service is supplied without creating ownership. This causes non acceptance by users or even quick failure in such service [Lüt-09, p. 461]. Moreover, in emerging countries, governments have put more priorities on regional and local conflicts, health care systems, and water and food supplies rather than provision of sustainable sanitation and wastewater management [Mss-09, p. 658].

5.5. Liquid waste management by solid-liquid separation

Solid-liquid separation equipment, as specified in chapter 3, sections 3.2.3 and 3.2.4, can be used either in the decentralized sanitation approaches in combination with secondary treatment equipment, e.g., soil filtration beds [Buu-99] and constructed wetlands [Kuj-06], or in the centralized sanitation approaches before secondary treatment equipment, e.g., trickling filters and activated sludge with filtration [Jef-00], [Neo-16].

5.5.1. Basic functions of solid-liquid separation

With respect to the ROSS module, in the collection, storage, and on-site treatment process, a solid-liquid separation equipment has two main functions:

- Reducing the organic load rate of the liquid waste that enters the SSF wetland to prevent or minimize any potential clogging of wetland filtration media.
- Providing cost-effective and reliable means for blackwater solids separation and storage in a safe and hygienic place, instead of harming health and wasting of key nutrients.

A solid-liquid separator (SLS) as a pre-treatment equipment has been designed, developed in the ROSS module, and realized in two decentralized prototypes in the Gaza Strip. The key functions of the SLS equipment are as follows:

a) Deals only with blackwater input products, e.g., urine, feces, dry anal cleansing, anal cleansing water, and toilet flushing water.
b) Receives blackwater from the household at all times of the day.
c) Distributes blackwater stream into equal sub-streams by passing through a distribution box. Then, all sub-streams pass through multi-interceptor double-jacketed tanks.
d) Separates blackwater solids by means of filter bags that are installed inside the inceptor tanks.
e) Stores blackwater solids in the filter bags for a period of 1–2 months based on the equipment design and the maintenance program as specified in chapter 6, section 6.2.1. Then, full bags are removed for further treatment and replaced by new ones. Not much reduction in solids volumes is expected in this short period, and the water content still may be high.
f) Allows blackwater liquid to pass through the filter bags and to flow by gravity or pumping to the nutrient adsorption tanks. Then, to the SSF wetland.

5.5.2. Development of solid-liquid separator equipment

The fundamental concept of the SLS equipment was inspired by development of “Rottebehälter” compost filters as specified in Chapter 3, Section 3.2.4. In the compost filters, blackwater solids are stored in a safe and hygienic manner until the favourable time for further processing and the production of soil conditioners. Other advantages of compost filters [Str-16] are as follows:

- No unpleasant odour in the liquid effluent as compared to the odour from anaerobic pre-treatment equipment, e.g., septic tanks.
- No biogas is produced because this equipment primarily supports aerobic conditions during the pre-treatment process.
- No skilled labours are required for the operation and maintenance. Short training is sufficient for the users.

Since efficient separation and easy accessibility of separated solids are key issues of any pre-treatment equipment, some modifications to compost filters have been made during development of the SLS equipment. These modifications were to overcome some weaknesses of the compost filters, including reduction of overall construction, operation, and maintenance efforts and costs. Table 5-1 compares key working parameters for both the compost filters and SLS.

Table 5-1: Comparison between compost filter "Rottebehälter" and solid-liquid separator.

Parameter	Compost filters	SLS	Parameter description
Overall depth	2 – 3 *m*	> 1 *m*	- Shallow depths require lower excavation costs. - Shallow depths require less construction and maintenance work. - Deeper depths are more risky and require more precautions during construction and operation.
Materials of main tank (chamber)	Concrete	Plastic	- Concrete tanks are heavier than plastic ones; therefore, more transportation cost is expected. - Concrete tanks require isolation work from both sides (outer and inner), which requires greater effort and cost. - Concrete tanks sometimes require casting in on-site, and pre-casted concrete tanks require heavy equipment for transportation. Plastic tanks are pre-manufactured and require normal transportation. - Cement for preparing concrete works may not be available in local markets, especially in the Gaza Strip. - Plastic tanks are commercially available in local markets.
Working period (active)	6 – 12 months	1 – 2 months	- Longer periods may cause washing out of too many nutrients.
Storage and removal period after working period (inactive)	6-12 months Storage then removal	Instant removal	- High reduction in solids volume is expected due to long storage time. - Loss of some nutrients, e.g., nitrogen, due to long storage period. - Instant removal requires more "hands on" maintenance.
Additives of dry bulking agents, e.g., straw or bark	Required	Not required	- Such additives are required to reduce moisture content for better composting, and improve air circulation for maintaining an aerobic condition to prevent offensive odour.
Filter bags maintenance	Weekly	Not required	- For addition of dry bulking agents in case of compost filters.
Filter bags weights	Heavier	Lighter	- Heavier bags require more "hands on" maintenance.

In the compost filters, the separation period and further storage period are 6–12 months and 6–12 months, respectively. However, in SLS, these periods were shortened to 1–2 months only. Although a short period increases the maintenance frequencies by removal of old filter bags and replacement of new filter bags, the maintenance frequency in the compost filters is still greater because they require addition of bulk agent materials, e.g., straw, on a weekly basis. The addition of these agent materials is not necessary in the SLS equipment.

5.6. Liquid waste management by subsurface flow wetlands

CWs have been accepted as an alternative decentralized low-cost treatment equipment to the conventional treatment equipment [USEPA-04, p. 21], particularly due to their beneficial use in small communities that cannot afford expensive treatment equipment [Poy-13].

5.6.1. Key functions of subsurface flow wetlands

CWs can play an important role in many ecological sanitation (Ecosan) concepts [Hof-11, p. 8] that consider human wastes as a valuable resource. Although CWs require careful design, operation, and maintenance, the key reasons to use CWs and to be integrated in a sustainable sanitation approach are as follows:

- CWs can save about 47% of overall water required in a household [Poy-13, p. 313]
- CWs can treat wastewater to produce a nutrient-rich irrigation water [SuSanA-08]
- CWs can yield an effluent of suitable quality for discharge to surface bodies of water or for various reuse applications according to WHO guidelines [WHO-06, p. 11]. Such reuse applications include flushing human excrement in toilets, irrigating backyard plants [Kro-16, p. 94], and recharging the groundwater aquifer [Afi-13, p. 5]. However, CWs cannot reach the treatment levels that are achieved by advanced wastewater treatment equipment [Kro-16, p. 94].
- CWs have additional benefits when built in a large scale, including nutrient harvesting and recycling; recreational and other human uses; protection of aquatic life and the health of marine ecology [Poy-13]; and accommodation of wildlife habitats [Rou-08, p. 187] when built in open public areas.
- CWs are a “green treatment”[Bri-07] equipment that can contribute to better local climate if integrated into urban water and wastewater management approach [Lüt-09].
- CWs do not rely much on energy for aeration and do not need chemicals for precipitation of the nutrient and bio-solids [Mug-08, p. 446].
- CWs are a reliable low-tech, low-cost treatment equipment due to their high efficiency for removal of organics, suspended solids, nitrogen, and pathogens [Ott-02], [Par-03], [Bri-07], [Mas-07], as well as heavy metals from wastewater [Crm-13].

5.6.2. Reasons for selecting SSF wetlands in ROSS module

On the basis of the scope of this thesis, the additional main reasons for selecting SSF wetland to be part of the ROSS module for liquid waste management are as follows:

- They have consistent treatment efficiency for domestic wastewater in the warm climate areas, e.g., the Mediterranean basin [Mas-07, p. 50], and for small communities and single households [Lan-10]. Regarding the example of the Mediterranean basin, very successful experiences with CWs have been reported for France [Bou-03], [Tro-14], Spain [Pui-07], Italy [Mas-08], [Mas-07], Czech Republic [Vym-02], Turkey [Mas-08], Morocco [Man-98], Egypt [Sha-13], and the Gaza Strip [Nas-06], [Afi-13].
- They provide a reliable treatment for domestic wastewater with no faecal sludge production after treatment. This is one of the main arguments in favour of SSF wetlands compared to most conventional treatment equipment, e.g., activate sludge units and trickling filters, which produce a secondary sludge, which is often discharged into the environment without treatment in most emerging countries [Hof-11, p. 10 f.].
- They have high capabilities for nutrient removal from wastewater and can be potentially used for improving wastewater quality [Bir-93, p. 19 f.].
- They can be built with a high degree of control as compared to FWS wetlands due to their flexibility in site selection, sizing, hydraulic flow, and retention time [Bir-93].
- The lifespan of small-scale wetlands can reach up to 15 years [Mas-08, p. 125].
- Their capital costs are less than that of conventional equipment of equal size. The major part of their capital costs are related to costs of filtration media (40% including transportation), bed excavation (30%), bed liner (15%), and vegetation (5%) [Vym-02, p. 643], if cost of needed land is neglected.
- They are attractive treatment alternatives for small- and medium-size communities in semi-urban and rural areas due to land availability and lower costs of lands [Bir-93]. However, land availability is a potential constraint for their realization in urban areas where high costs of land push their use to the margins of sanitation markets [Kro-16].
- The required space area of CW vegetation beds can be significantly reduced if the organic load of influent is lowered via pre-treatment equipment [Hof-11].
- Their operation and maintenance requirements are low and fairly easy due to minimal electrical and mechanical equipment; therefore, few specialized skills are required [Rou-08]. Maintenance requirements are limited to the filtration media, drainage pipe, and plant. The filtration media at the inlet zone can be replaced every 10 years or more; the bed filtration media can be washed and replaced when it is clogged by the bio-solids or attached bacterial films [Ott-99, p. 160]. The drainage pipes can be removed,

cleaned, and reinstalled if they are clogged. The plant roots should be kept above the bed bottom to prevent damage to the bed liner [Til-14, p. 119]. The plant stems can be cut from time to time. The produced plant waste can be used as animal feeder or used in compost production [Rou-08, p. 186].

- Energy consumption is typically limited to pumping stored liquid to another place either for reuse or further treatment, since most CWs are designed to function gravitationally [Rou-08, p. 186].

5.7. Bio-solid wastes management by Terra Preta sanitation

Inspired by the recent discovery of Terra Preta (TP) soils in the Amazon region, the first TPS approach was developed to produce a long-term and highly fertile soil conditioner with properties similar to those of TP soil [Fac-10].

The following sections present key issues of TPS that helped the author to develop the concept of the ROSS module, including TPS main features, TPS applicability to different types of faecal materials, and TPS integration to conventional water-based sanitation approach.

5.7.1. Main features of Terra Preta sanitation

TPS is a low-cost approach that is designed for dry sanitation, where the human excrements are handled and managed in the containment process and collection, storage, and on-site treatment process. TPS focuses on providing a low-tech sanitation approach, in which urine is separated from faeces in dry sanitation facilities, e.g., simple buckets, simple dry toilets, or urine diversion dry toilets (UDDTs). The separated faeces are manually mixed with charcoal, effective microorganisms EMs, and solid organic waste, e.g., food residuals. This mixture is used to produce a soil conditioner in a trial to copy the properties of TP soil through realizing natural processes—mainly lactic acid fermentation and vermi-composting. The separated urine can be used for activating the charcoal and to adsorb the dissolved nutrients contained in the urine [Sut-14]. Then, the urine can be used as a liquid fertilizer after a small amount of treatment.

Based on previous studies, TPS does not require more than airtight containers for storing human faeces and urine, charcoal, and microbial mixture in the lactic acid fermentation process. A relatively small space is needed to carry out the vermicomposting process for the entire mixture. TPS has high potential to be a low-cost sanitation alternative to the conventional approaches where there is a high opportunity to recover, recycle, and reuse plant nutrients.

5.7.2. Applications of Terra Preta sanitation

The application of TPS for different types of faecal materials, e.g., blackwater solids and faecal sludge, to produce Terra Preta-like substrate is currently under investigation. Findings have revealed that this substrate is suitable for reuse in farmland, plant production, and gardening, because it contains a high content of nutrients and has no toxic effects to plants [Böt-13]. Therefore, the early separation of faeces and urine that was deemed as a major condition for TPS to work [Fac-10] becomes irrational. Hence, trials to produce TP soil will be easier than the early separation process of faeces and urine [Pra-13]. However, urine separation toilets can still be used if urine is demanded to be directly used as a liquid fertilizer, because urine has minimal risk to human health [Esr-00].

For producing a Terra Preta like-substrate, an additional source of carbon, e.g., charcoal, is required to compensate for the carbon to nitrogen (C:N) ratio and water content. Particularly, when faecal materials are used as they are characterised by high water content and less carbon. In addition, involving charcoal in the composting process provide other valuable benefits, e.g., increasing the water holding capacity and reducing nutrient leakage [Bet-15] as discussed in chapter 3, section 3.4.3. Moreover, charcoal also can be made of woodchips or other agricultural wastes in low-tech and mobile stoves that can be locally manufactured with low costs from recyclables, e.g., metal cans [Sut-14].

The best place for application of TPS is where soil conditioners are needed and carbon-rich materials, e.g., woodchips and charcoal, are produced. Although the location for TPS application varies depending on the type of sanitation approach and availability of space, selection of a place that is close to waste production can significantly reduce transportation efforts and costs [Bet-15].

5.7.3. Integration of Terra Preta sanitation to conventional water-based approach

Contrary to dry sanitation, recent findings from research and development projects (R&D) have revealed that TPS can be successfully realized for conventional water-based sanitation approaches. For example, in Germany, TPS was integrated into public toilets at Botanical Garden of Berlin and to public toilets at the central train station in Hamburg [Sut-13]. TPS can be integrated at various parts of the sanitation service chain, e.g., on-site treatment or (semi) centralized treatment. However, TPS integration to new sanitation approaches in the planning and design phase would be more effective. Since solid organic wastes, e.g., food residuals, can be integrated into TPS after being separated from solid nonorganic wastes for producing Terra

Preta-like substrate, TPS can also be attached to the treatment facility of solid organic waste. However, TPS integration to current water-based sanitation approaches requires some retrofitting and remodelling to replace existing equipment, e.g., flushing toilets or/and urinals, and incorporating new equipment that facilitates separation and collection of various wastewater and solid organic waste streams [Sut-13]. Particularly in urban areas, this retrofitting to the whole centralized approach would create expensive costs and intensive efforts, and could face difficulties regarding the public acceptance [Kau-07, p. 115].

R&D project findings have also revealed that TPS can significantly contribute to efficient reuse and sustainable management of natural resources, including water and nutrients. Hence, contribution to close loops on water and nutrient cycles and to MDG targets on providing safe and appropriate sanitation for all people might be achieved [Sut-14].

In the ROSS module, TPS is integrated into a conventional water-based sanitation at the household level in the Gaza strip, where the household wastewater is collected and stored in a septic tank; no whole sanitation service chain is provided; and no water-based sewer and no connection to any central treatment facility is provided. Additionally, a mixture of solid organic and non-organic wastes is periodically collected and transported from households to central landfill via municipality trucks.

Bio-solid waste separation increases the production efficiency of Terra Preta-like substrate as well as reduces solids precipitation in the water-borne sewers [Bet-15]. In the ROSS module, separation of wastewater streams, i.e., blackwater from greywater, requires replacement of old pipes that mix all types of wastewater steams by new pipes for each stream. The use of solid-liquid separation equipment is required for collecting blackwater solids with less water and high nutrient contents.

6. Realization and monitoring of the resource-oriented sustainable sanitation module

The realization and monitoring part of the ROSS module, developed in this thesis, consists of two main parts according to the module concept as specified in Chapter 5. These take into consideration the management of both bio-solid wastes and liquid wastes. Firstly, on-site treatment and reuse of liquid wastes, i.e., household greywater and blackwater liquid, are researched through design, development, and realization of two decentralized prototypes in the Gaza Strip. The performance and efficiency of these prototypes is monitored through sample collection, laboratory testing, and results analysis for one prototype. Secondly, on-site treatment and recycling of faecal bio-solid wastes is researched through production of a Terra Preta-like substrate. The quality of the Terra Preta-like substrate is investigated by sample collection, laboratory testing, and results analysis.

6.1. Description of the study area

Realization of any sanitation approach, or module, is a key issue in order to find a sustainable solution in a specific location where relevant information can be gathered for further adaptation and future upgrades [SuSanA-08, p. 10]. Two decentralized prototypes were designed, developed, realized, and monitored in two households in the eastern part of Rafah governorate, Gaza Strip as shown in Figure 6-1. This part of the Rafah governorate is characterized as a semi-urban or rural area where the majority of people work in agricultural activities. This area is not served by any conventional centralized sanitation as the coverage, in terms of access to water-borne sewers and central WWTP, reaches 70% in Rafah governorates [CMWU-10]. Therefore, residents of the region mainly depend on conventional wet on-site approach for handling their wastewater. Flushing toilets are used in the containment process, while septic tanks, percolation tanks, or some pit latrines are used for the collection, storage, and on-site treatment process. Rarely, vacuum trucks operated by individuals are used for emptying, transporting, and disposing of wastewater from these septic tanks and pit latrines. However, most often such maintenance is not carried out, resulting in surface flow of wastewater that poses health and environmental problems. Improper design and lack of maintenance allows wastewater to infiltrate into sub-soil layers, carrying pollutants, i.e., pathogenic microbes, and soluble elements, e.g., Cl, NO_3- and PO_4, which can contaminate the groundwater, as specified in Chapters 2 and 3.

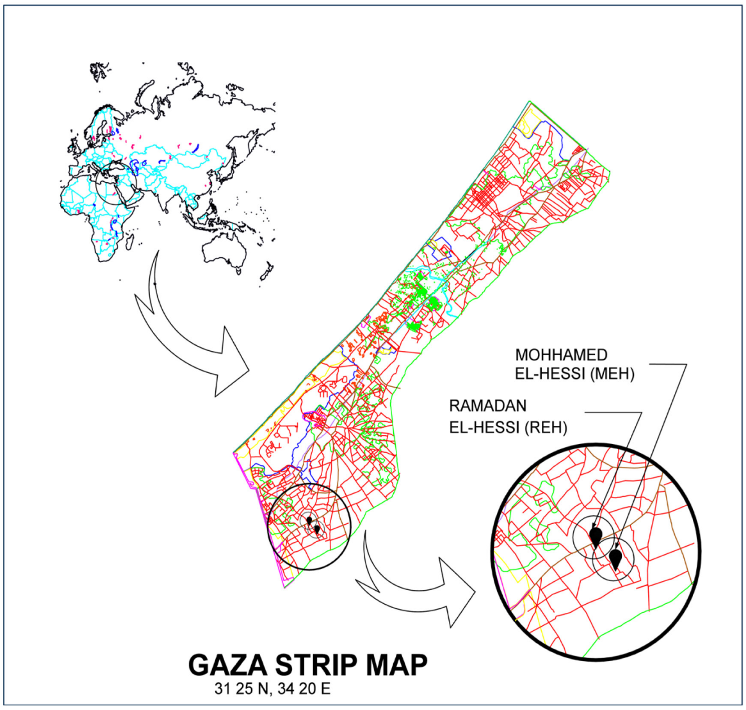


Figure 6-1: Area of study and locations of the two prototypes.

The groundwater is deemed as the only main source of water in the Gaza Strip for supplying domestic, agricultural, and industrial needs. The surface water is very limited or not available. However, the groundwater is contaminated by high levels of salinity and nitrate that exceeds the WHO standard recommended concentration of less than 50 *mg/l.* The high concentration of nitrate is linked to lack of proper wastewater collection and treatment facilitates, and intensive use of industrial fertilizers and pesticides in agriculture [CMWU-10].

The Gaza Strip is a small part of Palestinian territory, which is located on the eastern coast of the Mediterranean Sea, between longitudes 34° 2" and 34° 25" east, and latitudes 31° 16" and 31° 45". It is bordered by Egypt on the southwest and Israel on the east and north. The land area is about 365 km^2. In 2016, the population exceeds two million in the Gaza Strip [IMEMCNews-16]. This makes the Gaza Strip one of the most densely populated areas in the world (ca. 5480 $persons/km^2$).

The current situation of water resources in the Gaza Strip hinders the transition towards sustainability. Significant changes and a paradigm shift in urban water and sanitation are urgently required [Esh-16].

6.2. Realization of modules

The realization of the ROSS module includes the design considerations and construction details, i.e., the materials specifications and the module components as described in the following sections. Based on the sanitation service chain as specified in Chapter 5, Section 5.3, the module handles and treats the liquid waste and bio-solid wastes separately. Figure 6-2 represents the main components of the module equipment, and their associated processes in the service chain. More details about the design and components of the ROSS module for MEH and REH prototypes can be found in Annexes I.I, I.II, I.III, and I.IV.

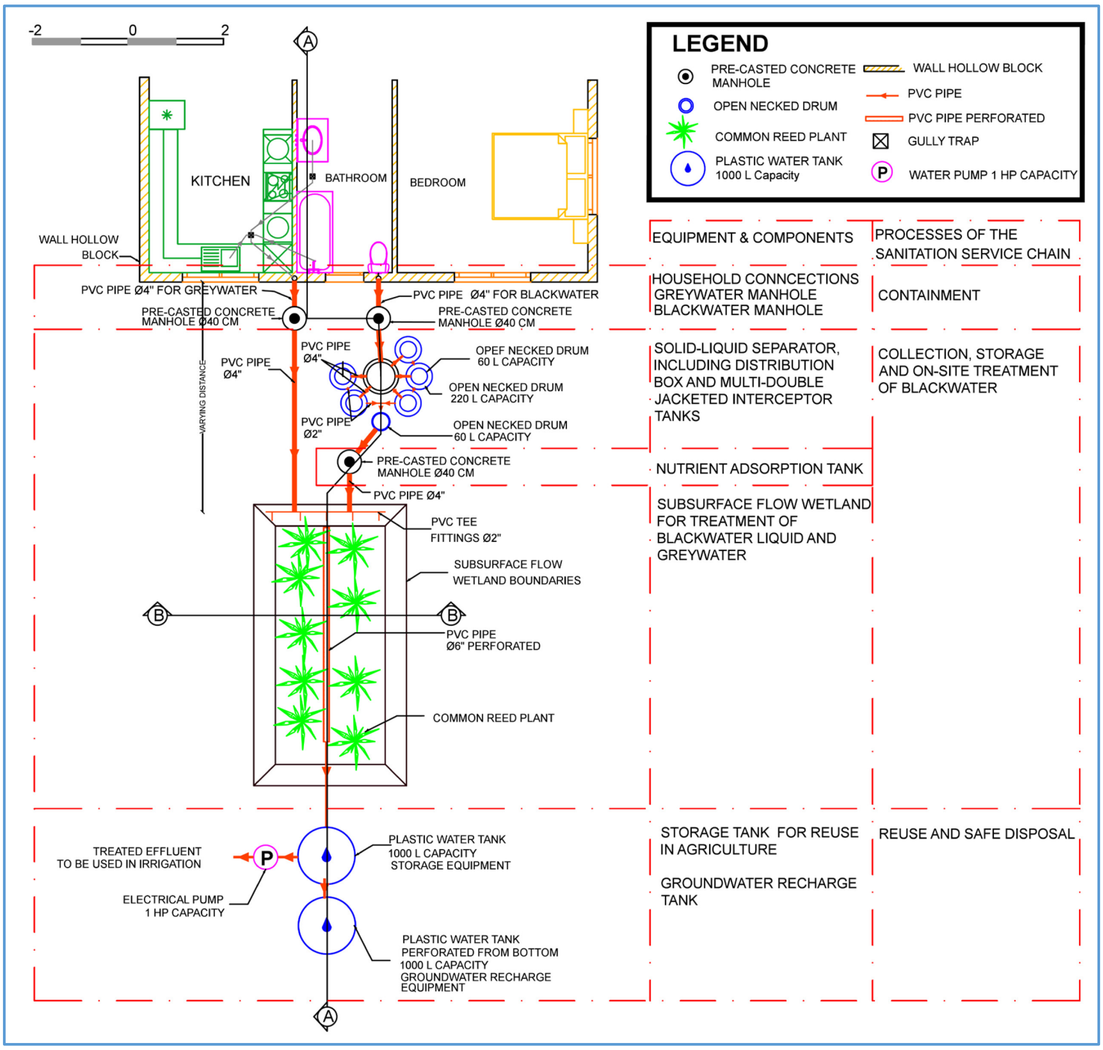


Figure 6-2: Schematic design for components, equipment, and associated processes in the service chain of the ROSS module. Design: Alnahhal, Samir, 2017.

6.2.1. Solid-liquid separator for liquid waste treatment

As specified in Chapter 5, Section 5.5, the SLS works as a per-treatment equipment, by which the blackwater solid, e.g., faeces and toilet papers, are separated and safely and hygienically stored until a suitable time for further treatment processes. The main concerns in the design, development and construction of SLS equipment include:

- Design considerations and parameters.
- Materials specifications, components and construction details.

Design considerations and parameters

The SLS equipment consists of multi-interceptor double jacketed tanks with a distributing box. The design considerations include:

- Volume of blackwater solids.
- Capacity and number of interceptor double jacketed tanks with distribution box.

1) Volume of blackwater solids

Blackwater solids are those solids contained in the blackwater, including faeces and dry anal cleansing materials, e.g. toilet paper. Faeces is the major part of blackwater solids, which has been estimated at about 50 litres per person per year (*l/p.y*) [Ott-01], [Win-04], [Gan-15].

The volume of blackwater solids (V_S) is an important concern in the design of the capacity and number of interceptor double jacketed tanks. This volume can be estimated based on the number of persons who are going to use the decentralized module and the estimated volume of solids per unit time.

For both prototypes, the VS is calculated in Table 6-1 based on the following assumptions:

Table 6-1: Volume of blackwater solids in the separation and storage periods for both prototypes in Gaza Strip.

Nr.	prototype module name	Actual Number of users	Design number of users	Separation and storage period *(day)*	Faeces volume per person per year *(litre)*	Volume of blackwater solids (V_{TS}) in separation and storage period *(litre)*
		[1]	[2]=[1] + [1]*25%	[3]	[4]	[5]= [2] * [3] * [4]/ 365
1	Mohammad El Hessi (MEH)	24	30	60	50	247
2	Ramadan El Hessi (REH)	17	21	60	50	173

- Faeces volume is the blackwater volume, which is estimated at 50 *l/c.y.*

- Volume of dry anal cleansing materials, e.g. toilet paper, is neglected because its volume is very small compared to that of faeces, and it may be also included in the estimation of faeces by [Ott-01], [Win-04], and [Gan-15].
- The time period of two months is the time for separation and storage of solids in the interceptor tanks. The author suggests reducing this period to one month if the number of users exceeds 40 persons.
- A safety factor of 25% is added to the number of users in order to take into consideration any population increase, future expansion, and underestimation of faeces volume.

2) Capacity and number of interceptor double jacketed tanks with a distribution box

The interceptor double jacketed tanks include some active interceptor tanks and one emergency interceptor tank. The number of active tanks depends on the volume of blackwater solids, Vs. Each interceptor tank (active and emergency) consists of two plastic open necked drums. A smaller size drum is hung inside the bigger drum in a flexible way that allows its removal and reinstallation. A filter bag is fixed inside the smaller drum. This works as a screener tank to separate solids from liquids and store them inside the filter bags. The larger drum works as a container tank as shown in Figure 6-3.

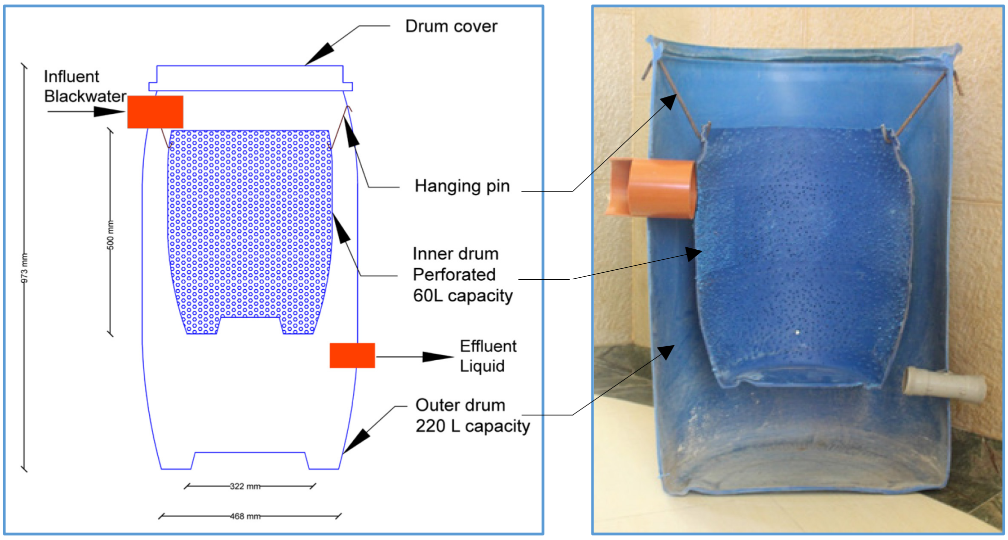


Figure 6-3: Cross-section schematic of interceptor double jacketed tank. Design and photo: Alnahhal, Samir, 2017.

Commonly, a distributed box or "D-Box" lies between the collection, storage, and pre-treatment equipment, e.g., septic tank or Imhoff tanks, and the drain-fields, e.g., soil adsorption beds or constructed wetlands. The D-box serves as a tool or equipment that can evenly distribute the wastewater stream into sub-streams among these drain-fields [Lee-04], [URI-16]. Generally, the D-box has a rectangular shape with one inlet and more than one outlet. For both prototypes, the distribution box was located before the collection, storage, and pre-treatment equipment, which are the interceptor tanks in the ROSS module. Similar to the conventional D-Box, the distribution box has one inlet and more than one outlet, but it is circular not rectangular. The inlet is connected to household connection pipes that carry the blackwater, while its outlets are connected to the interceptor tanks.

The key design criteria of calculating the number of active interceptor tanks includes the volume of blackwater solids (V_S) and the volume sizes of container drums and screener drums. Based on drum availability in local markets, a drum volume of 60 *l* is used as a screener drum. While a drum volume of 220 *l* is used as a container drum. Table 6-2 shows the calculations of the number of active interceptor tanks for both prototypes, MEH and REH.

Table 6-2: Calculated and designed number of active interceptor tanks for both prototypes (MEH and REH).

Nr.	prototype module name	Volume of blackwater solids in separation and storage period (V_{TS})* *(litre)*	Inner drum size *(litre)*	Outer drum Size	Calculated number of interceptor tanks *(Nr.)*	Designed number of active interceptor tanks** *(Nr.)*
		[1]	[2]	[3]	[4]=[1] / [2]	[5]
1	MEH	247	60	220	4.11	6
2	REH	173	60	220	2.88	4

* As calculated in Table 6-1.
** The calculated number of interceptor tanks rounded to the next even number.

The number of active interceptor tanks is designed to be an even number because each pipe that is connected to the outlet of the distributing box is also connected to two interceptor tanks at the other end. This arrangement was suggested by the author to reduce the number of outlet pipes that are required to be connected to the distribution box. This minimizes the number of distribution boxes, and the associated cost and space needed for their construction. Based on calculation, for an odd number of active interceptor tanks, an additional tank is required to be added to the arrangement. This addition of one tank obtains the design number of active tanks.

For emergency considerations, one additional interceptor tank is included in the development and implementation of the SLS equipment. The emergency tank is connected to the distribution box at a level above the inlet and other outlets that are connected to the active tanks. Therefore, the additional tank only operates in case of any clogging problems in the active interceptor tanks or in the distribution box due to bulk solids that may be allowed to enter the SLS equipment.

As shown in Figure 6-4 (a) and (b), the blackwater passes into active interceptor tanks, and solids are separated and stored inside the filter bags. The liquid effluent drains from these bags and passes from the screener tanks to the container tank. The effluent can then be collected at the bottom of the container tanks by gravity to proceed to the next treatment equipment, i.e., the nutrient adsorption tank. Electrical pumps can also be used when the liquid levels are not sufficient to produce flow by gravity. However, in both prototypes, the liquid is designed to flow by gravity to minimize the energy requirement and its associated costs. Using gravity based flow can overcome problems of securing a source of electrical power at all times of the day, which is an issue in most rural areas of emerging countries, particularly in the Gaza Strip.

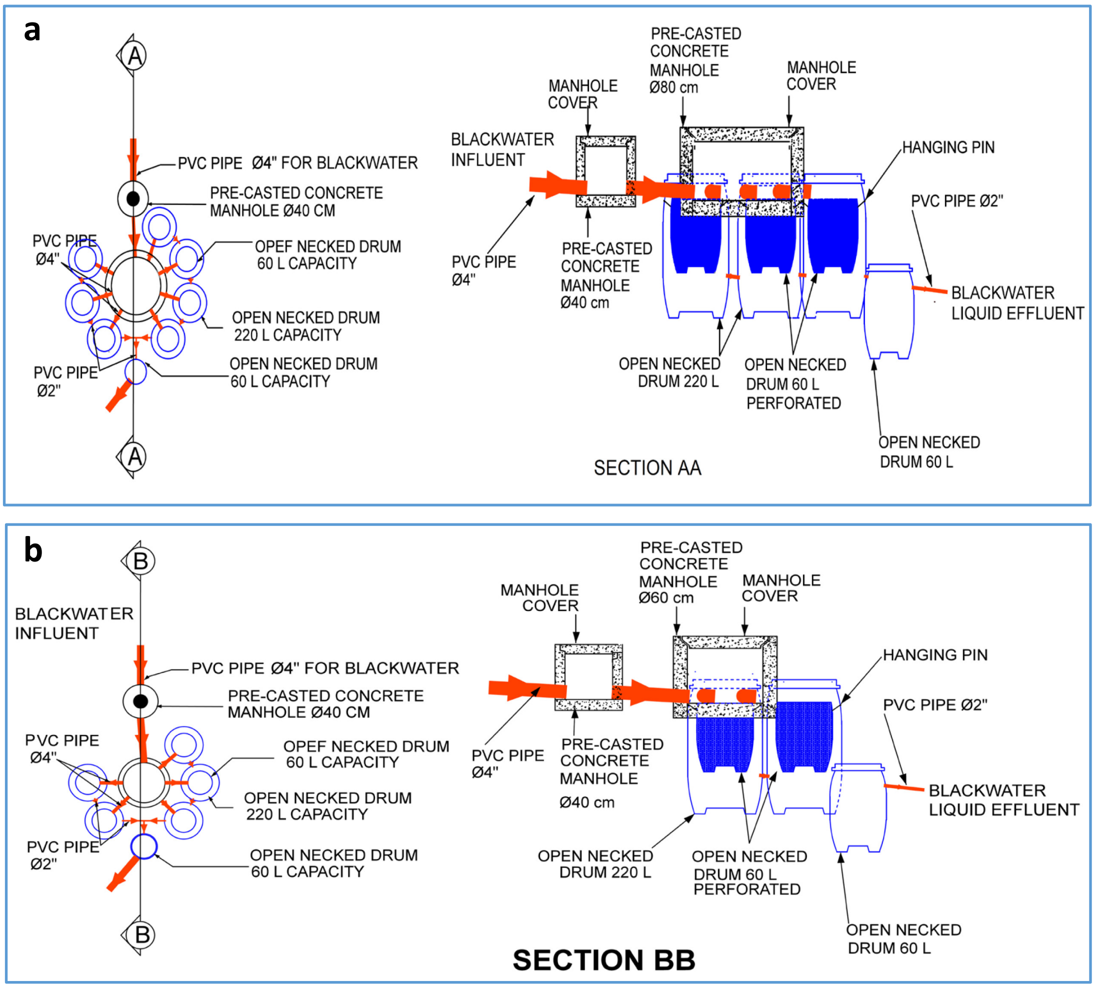


Figure 6-4: Schematic design of SLS equipment in (a) MEH prototype (b) REH prototype.

Materials specifications, components, and construction details

The solid-liquid separator consists of two main components, including:

- Distributing chamber
- Interceptor double jacketed tanks

1) Distribution box

A distribution box can be made of concrete or plastic. Internationally, several commercial distribution boxes are available and brought to markets. Selection of a certain box depends on the number of outputs that would eventually be connected to drain-fields or to interceptor tanks.

In both prototypes, commercial pre-casted concrete manholes were used to work as a circular shape distribution box as shown in Figure 6-5. The concrete manhole is not made for such purpose but it is arranged to perform the even distribution of blackwater by drilling through the manhole side wall and installing the inlet and outlet pipes, and by levelling the manhole base. For levelling of the base, plain concrete paste is used. Contrary to conventional distribution boxes, this levelling prevents any stagnant water inside the manhole, as the stagnant water can influence the biological properties of blackwater if it remains in the manhole for too long. Through this arrangement, shortages of commercial distribution boxes in local markets can be overcome, specifically in the Gaza Strip.

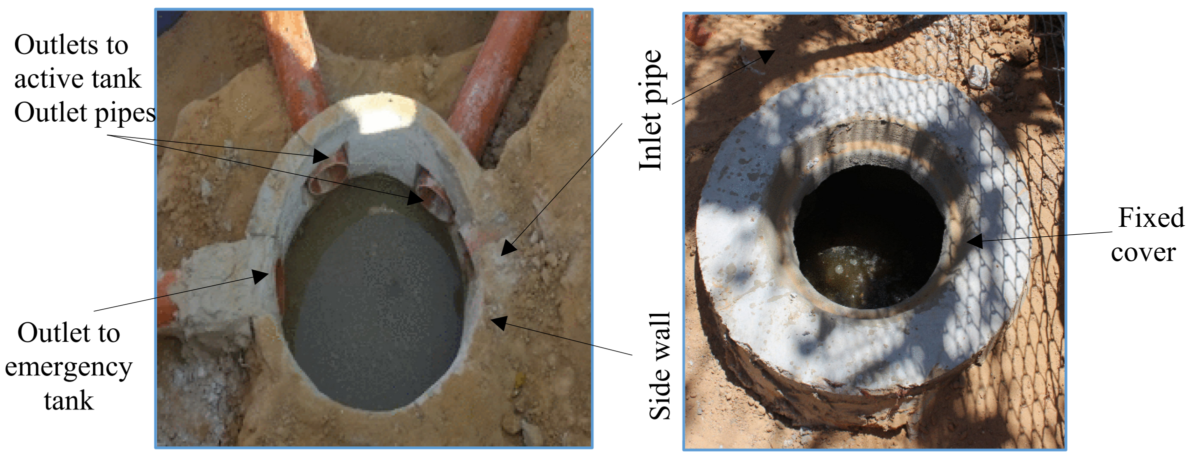


Figure 6-5: Circular shape distribution box under construction. Photo: Alnahhal, Samir, 2017.

Pre-casted concrete manholes of 80 *cm* and 60 *cm* diameter were used in MEH and REH prototypes, respectively. The author suggests using a concrete manhole of diameter 60 *cm*, if the outlets are more than three outlets (two outlets for active tanks, one outlet for the emergency tank), as is the case for the REH prototype. While a concrete manhole of diameter 80 *cm* can be used if the outlets range from four to seven as is the case for the MEH prototype. In case the number exceeds seven outlets, a new arrangement of three manholes may be required, where the first manhole of diameter 60 *cm* can evenly distribute the blackwater among the two manholes that can have a diameter of 60 *cm* or 80 *cm* based on the number of outlets.

The inlet level is 5 *cm* higher than the outlets that are connected to the active tanks at the same level. While the outlet pipe that is connected to the emergency tank can be at the same level of the inlet, or 5 *cm* higher. Pipes of diameter 4” inches (110 *mm*) that are locally made of Polyvinyl Chloride (PVC) were used for the inlet and outlets. In addition, specific consideration should be given to the placement and installation of the manholes with inlet and output pipes, as tilting of one side of the distribution box is a common problem after some years of operation. A concrete base of 5 *cm* can be made underneath the manhole base to avoid tilting. The inlet and outlet sides can also be casted using plain concrete paste.

2) Interceptor double jacketed tanks

The interceptor double jacketed tanks are the key component of the solid-liquid separation equipment. Each interceptor tanks consists of one container tank and one screener tank that includes a filter bag, as shown in Figure 6-6 (a and c), and Figure 6-6 (b and d).

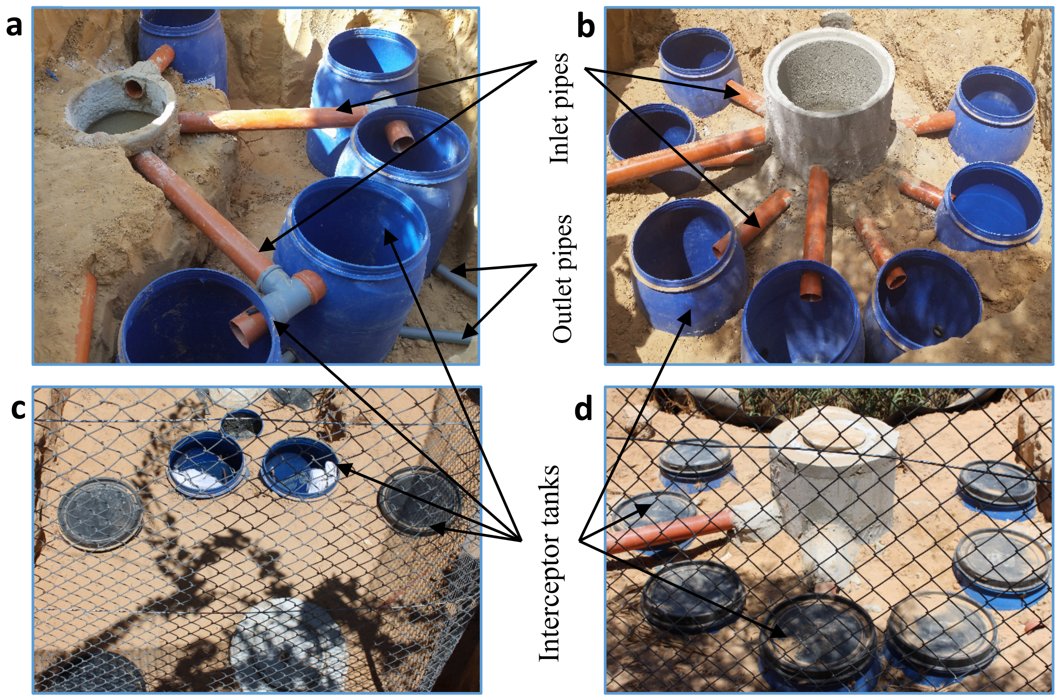


Figure 6-6: SLS under construction in (a) REH prototype; (b) MEH prototype. Functioning SLS equipment in (c) REH prototype; (d) MEH prototype. Photo: Alnahhal, Samir, 2017.

The container and screener tanks are open necked drums made of High Density Polyethylene (HDPE). Different sizes of plastic open-necked drums are available in local markets with volumes ranging from 30 to 2000 *l*.

A drum of volume 220 *l* was used as a container tank are, while 60 *l* drums was used as screener tanks. The screener tank is hung inside the container tank in a flexible way to facilitate the removal and reinstallation of the screener tanks for maintenance and cleaning purposes. The screener tank was arranged to have no covers to make the removal and replacement of filter bags easier. The screener tanks are also perforated by small holes of diameter 1/8” (3.2 *mm*) at the bottom and sides to allow the passage of liquid from the filter bags to the container tanks.

All inlets of the active interceptor tanks that are connected to the outlets of the distribution box should have the same level, where PVC pipes of diameter 4” (110 *mm*) can be used. These inlets are connected in parallel to receive the same quantity of blackwater from the distribution box. The outlets of the active tanks are connected in series to collect the liquid drained from screener tanks, where PVC pipes of diameter 2” (50 *mm*) are used. The outlet of the emergency tank is also connected to those of the active tanks. All inlet and outlet pipes have a slope of 1.5 *cm* to every 1 m along their lengths.

The filter bags that are used for blackwater solids separation and storage for two months are made of Polyethylene (P.E.) and of volume 60 l (45 cm width x 85 cm depth) as shown in Figure 6-7. New bags can be used to replace the full bags, and the solid contents can be removed and stored in air-tight containers for additional treatment via LAF and composting.

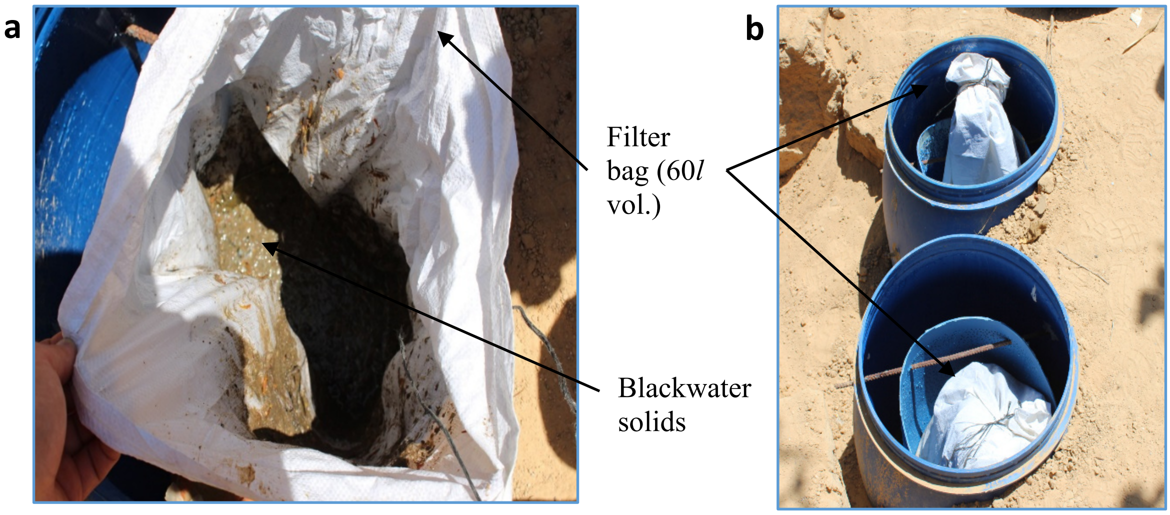


Figure 6-7: (a) Filter bag; (b) interceptor tanks include filter bags. Photo: Alnahhal, Samir, 2017.

6.2.2. Subsurface flow wetlands for liquid waste treatment and reuse

The major concerns in the design and construction of the subsurface flow (SSF) wetland that is used in the ROSS module for on-site secondary treatment and reuse of liquid wastes, e.g., greywater and liquid blackwater, include:

- Design consideration and parameters.
- Material specification, components and construction details.

Design consideration and parameters

The main parameters of the SSF wetlands design and development of both MEH and REH are as follows:

- Pre-treatment process
- Flow pattern
- Hydraulic flow
- Vegetation bed

1) Pre-treatment process

For on-site treatment of wastewater, the pre-treatment is a fundamental process when SSF wetlands are used prevent clogging of their filtration media. However, in many cases in emerging countries, pre-treatment does not receive enough attention from the operators, eventually causing the deterioration of effluent quality [Vym-02]. The pre-treatment in the ROSS module is designed not only to separate and remove the blackwater solids, but also to collect and store these solids until suitable time for treatment and reuse as specified in Chapter 5, Section 5.5 and in Chapter 6, Section 6.2.

2) Flow pattern

For both prototypes, the SSF wetlands were designed for horizontal flow within the bed. The influent flow enters the wetlands from the side by two separate pipes (one for the greywater and one for blackwater liquid). Then, the flow is combined together in one pipe, which is connected to a number of manifold pipes along the width of the wetland bed. This arrangement is used to facilitate a wider distribution of liquid along the bed. This arrangement is commonly used in the horizontal subsurface flow wetlands (HSSF), as shown in Figure 6-8. The effluent flow is designed to be collected from the bottom of the bed in a way similar to that used in the vertical subsurface flow wetlands (VSSF), as shown in Figure 6-8.

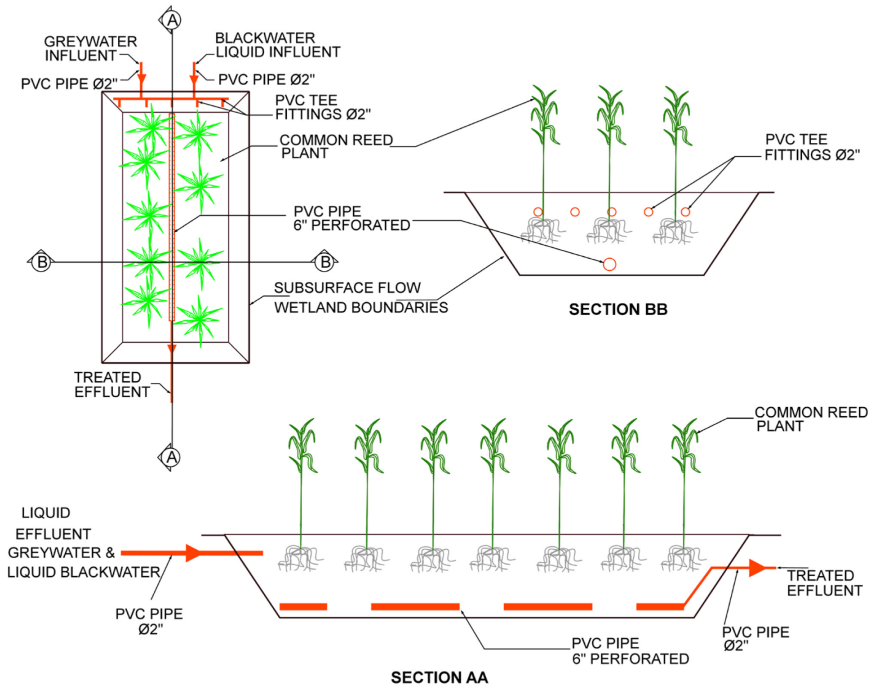


Figure 6-8: Inflow and outflow pattern of the SSF wetland. Design: Alnahhal, Samir, 2017.

3) Hydraulic flow

The hydraulic flow includes all sources of water and wastewater that enter as inflow and leave as outflow from the wetland bed. The total inflow and outflows are presented in the general water balance Eq. (6-1):

$$I - O = \Delta W / \Delta t \quad \text{.......... (6-1)}$$

Where,

I = inflow (m^3/day) duration time, Δt
Q_w = outflow (m^3/day) duration time, Δt
Q_p = change in water volume (m^3)
Δt = duration time

The total inflow is the average daily flow of greywater and liquid wastewater and the precipitation. The precipitation should be calculated based on 2-year, 24-hour rain event, or roughly 5 inches per day [Kop-07]. The total outflow includes the evaporation and plant transpiration and water uptake. The liquid waste balance of the SSF wetland is presented in Eq. (6-2):

$$Q_\Delta = (Q_p + Q_w)_{in} - (Q_e + Q_{wu})_{out} \quad \text{.......... (6-2)}$$

Where,

Q_Δ = the total amount of flow that the wetland needs to contain during major storm events (m^3/day)

Q_w = average daily flow of greywater and liquid wastewater (*m^3/day*)
Q_p = average daily rate of precipitation (*m^3/day*)
Q_e = average daily rate of evaporation (*m^3/day*)
Q_{wu} = average plant transpiration and water uptake (*m^3/day*)

In order to calculate Q_Δ in Eq. (6-2) for both prototypes, the surface area of the wetland, i.e., the vegetation bed, must be assumed based on the number of users. Since blackwater solids are separated, only greywater and liquid blackwater flow in the wetland. The surface area recommended by [Ott-99] and [Til-14] is 2.0 *m^2* per *p.e.* for greywater treatment used as shown in Table 6-3.

Considering the area of study in the Gaza Strip, the average daily rate of precipitation (Q_p) is about 327 *mm/year* as reported by the Palestinian Centre Bureau of Statistics (PCBS) [PCBS-14], whilst the average daily rate of evapotranspiration ($Q_e + Q_{wu}$) is about 77% of (Q_p) as recommended by [Ais-14]. Moreover, the average number of rainy days in the Gaza Strip does not exceed 50 days [Hal-08].

Table 6-3: Total flow rate of the SSF wetlands for both prototypes.

Nr.	Prototype module name	Actual Number of persons per family	Design number of persons per family	Calculated average wastewater flow *(m^3/day)*	Average precipitation rate in the bed, $(Q_p)^*$ *(m^3/day)*	Average evapo-transpiration rate, $(Q_e + Q_{wu})^*$ *(m^3/day)*	Total daily flow, (Q_Δ) *(m^3/day)*
		[1]	[2]=[1]* 25%	[3]=[2]*90 *(l/d)**80%	[4]=[2]* 2 *(p.e.)* *327 *(mm)** 2 day HRT / (50 *(day)**1000)	[5]=[4]* 77%	[6]=[3]+ [4]-[5]
1	(MEH)	24	30	2.16	0.78	0.60	2.34
2	(REH)	17	21	1.52	0.56	0.43	1.65

Based on the number of users, the average daily wastewater flow is assumed to be 80% of average water consumption as reported in [Afi-06] and as assumed by the Palestinian Water Authority (PWA) [PWA-12]. While the average water consumption is 90 litter per person per day (*l/p.d*) as assumed by PWA [PWA-14], [PWA-15].

For treatment of domestic wastewater, the vegetation bed can be designed for a minimum storage of two days as the hydraulic retention time (HRT) and can be up to six days depending on the level of treatment desired. Since the removal of BOD and TSS that can occur after two days is marginal [Kop-07], the HRT of two days is used to calculate Q_Δ in Eq. (6-2) as recommended by [Ree-93].

4) Vegetation bed

a. Depth and bed slope

The depth (d) of the vegetation bed is basically derived from the maximum root and rhizome depth of the emergent plants that are used for water treatment. These plants have the advantage of being in contact with influent liquid to maintain aerobic conditions throughout their roots zone and to minimise anaerobic zones [Ree-93], [UN-HABITAT-08]. The shallower depth is not recommended because the roots might harm the bed lining. In the case of the common reed "Phragmites Australis", the designed bed depth can range from 0.6 m [Ree-93] to 1.0 m [Vym-02]. In both modules, common reeds were used. However, the depths of the vegetation bed were designed as 0.9 m and 0.75 m for MEH and REH modules respectively.

The slope of the bottom of the bed is commonly considered in the design of the SSF wetlands to ensure an acceptable hydraulic gradient of the flow in order to maintain a horizontal flow along the length of the bed. However, it is not practical or even difficult to precisely construct SSF wetlands for a specific bed slope due to high variability in the filtration media and in construction techniques [Ree-93]. The SSF wetlands do not require a high bed slope when gravel is used as the filtration media [Vym-02]. For both modules, gravel is used and the bed slope is designed with slope ≤ 1%.

b. Filtration media

The filtration media of the CW vegetation bed should: (1) have a suitable porosity and a high hydraulic conductivity to provide efficient infiltration, even distribution, and collection of influent and effluent liquid, respectively; (2) facilitate and improve plant growth [Ree-93]; (3) provide high surface area for the efficient growth of microorganisms; and (4) be able to filter and trap bulk solid particles [UN-HABITAT-08]. Sand and gravel can be used as a filtration media for filling the vegetation bed [Hof-11]. In our pilot modules, gravel was used as a filtration media. The gravel has a porosity ranging from 38% to 45%, and a hydraulic conductivity ranging from 7500 to 100,000 m/day based on the size of the gravel [Ree-93], [Kop-07]. Although for large-scale systems and systems with a large number of units that are to be filled with the same kind of gravel, field and laboratory testing for the porosity and hydraulic conductivity are highly recommended [Ree-93].

c. Surface area dimensions

The wetland area can be assessed based on two design methods: volume-based or area-based [Wll-06]. The volume-based method depends on a hydraulic retention time to determine the reduction of wastewater pollutants, e.g., SS, BOD, nitrogen phosphorus. The area-based method uses the overall surface bed area to assess these pollutants.

The first-order plug flow kinetic model is recommended for design of on-site wetlands for BOD removal [Ree-93], [Kad-09]. The general form of the model is presented in Eq. (6-3):

$$\frac{C_e}{C_o} = e^{(-K_T t)} \qquad (6\text{-}3)$$

Where:

C_e = effluent BOD_5 (mg/l)
C_o = influent BOD_5 (mg/l)
K_T = temperature dependent rate constant (d^{-1})
T = Temperature of liquid in the wetland ($°C$)
t = hydraulic retention time (d)

The constant (K_T) depends mainly on temperature [Ree-93] and is presented in Eq. (6-4)

$$K_T = K_{20}(\theta)^{(T-20°)} \qquad (6\text{-}4)$$

Where:

θ = temperature coefficient for rate constant, equals 1.06
K_{20} = temperature coefficient for rate constant, equals 1.104 (d^{-1})

The factor of hydraulic residence time (t) in Eq. (6-3) can be represented as in Eq. (6-5)

$$t = \frac{nLWd}{Q} \qquad (6\text{-}5)$$

Where:

L = length of bed (m)
W = width of bed (m)
n = effective porosity of media ($\%$)
d = average depth of liquid in bed (m)

Combining equations (6-3), (6-4), and (6-5), produces the final form of the plug flow model as presented in Eq. (6-6), where the bed surface area can be calculated.

$$A_s = (L)(W) = \frac{Q_\Delta[ln(C_o/C_e])}{K_T dn} \qquad (6\text{-}6)$$

It is believed that the constant (K_T) for SSF wetlands is high because of the large surface area of the filtration media, which supports the growth of microorganisms. It is also believed that these microorganisms are responsible for providing most of the treatment responses.

[Ree-93] recommended using the conservative value of the rate constant (K_T) and temperature coefficient (θ) as 1,104 d-1 and 1.06 respectively. The temperature coefficient (θ) increases about 10% per 1 ºC [UN-HABITAT-08]. These values strongly depend on the rate of organic loading and level of pollutant removal [Ree-93], [Sir-06]. For BOD removal, [Sir-06] recommended using the constant (K_{20}) as 0.678 d-1 and the coefficient (θ) as 1.06, whilst for ammonia nitrogen, vales of (K_{20}) and (θ) are 0.218 d-1 and 1.048 respectively.

For BOD removal in both modules, Eq. (6-6) is utilized to determine the surface area of the vegetation beds. The value of the rate constant (K_T) is calculated based on Eq. (6-4) where the constant (K_{20}) is 0.678 d-1 and the coefficient (θ) is 1.06. The temperature of the liquid in the bed (T) is 17.64 °C, which is derived from the average annual temperature in the Gaza Strip as reported by [Rrd-12].

The influent BOD_5 (C_o) can be derived from the average of BOD*5* of the raw wastewater and amounts to 541mg/l, as measured for the Gaza Strip by [Nas-10]. A 40% reduction in the BOD_5 of raw wastewater is assumed to be achieved in the pre-treatment process by using typical septic tanks, with BOD_5 removal efficiency ranging from 30% to 50% [USEPA-02] or from 30% to 40% [Til-10].

The effluent BOD5 (C_e) is designed as 35 mg/l, which is less than the standard limits set by the Palestinian Standards Institute (PSI) for irrigation from 40 to 60 mg/l and groundwater recharge of 40 mg/l. Based upon Eq. (6-6) and previous assumptions, the surface areas of the vegetation beds (A_s) are determined as 14 m2 and 12 m2 for MEH and REH prototypes respectively

d. Aspect ratio

Aspect ratio $(L{:}W)$ is the ratio of length (L) to width (W) of the surface area of the wetland. The aspect ratio is important in the design of SSF wetlands. Although it was suggested in the past to have a high aspect ratio in order to achieve a high level of pollutant removal, e.g., BOD_5 and TSS, recent studies concluded no relation between the aspect ratio and the removal efficiency for these pollutants. Many old SSF wetlands that have a higher aspect ratio of (10:1) did not improve the performance, and even worse, they failed to maintain an adequate hydraulic gradient and could not prevent surface flow problems [Ree-93]. Using lower aspect ratio has proved its effectiveness in avoiding the clogging at the inlet zone of the wetland because a wider distribution of the influent liquid along the bed width can be maintained [Vym-02].

Generally, aspect ratio ranges from (0.4:1) to (3:1) are acceptable. Selection of a certain aspect ratio relies on the site topography [Ree-93] and land availability [Afi-15].

In both modules, the aspect ratio of (2:1) is used. According to this aspect ratio and the calculated surface areas from Eq. (6-6) the dimensions of the bed (length and width) are calculated as 5.3 m length (L) and 2.6 m width (W) in the MEH prototype as shown in Figure 6-9 (a), and 4.9 m length and 2.4 m width in the REH prototype as shown in Figure 6-9 (b).

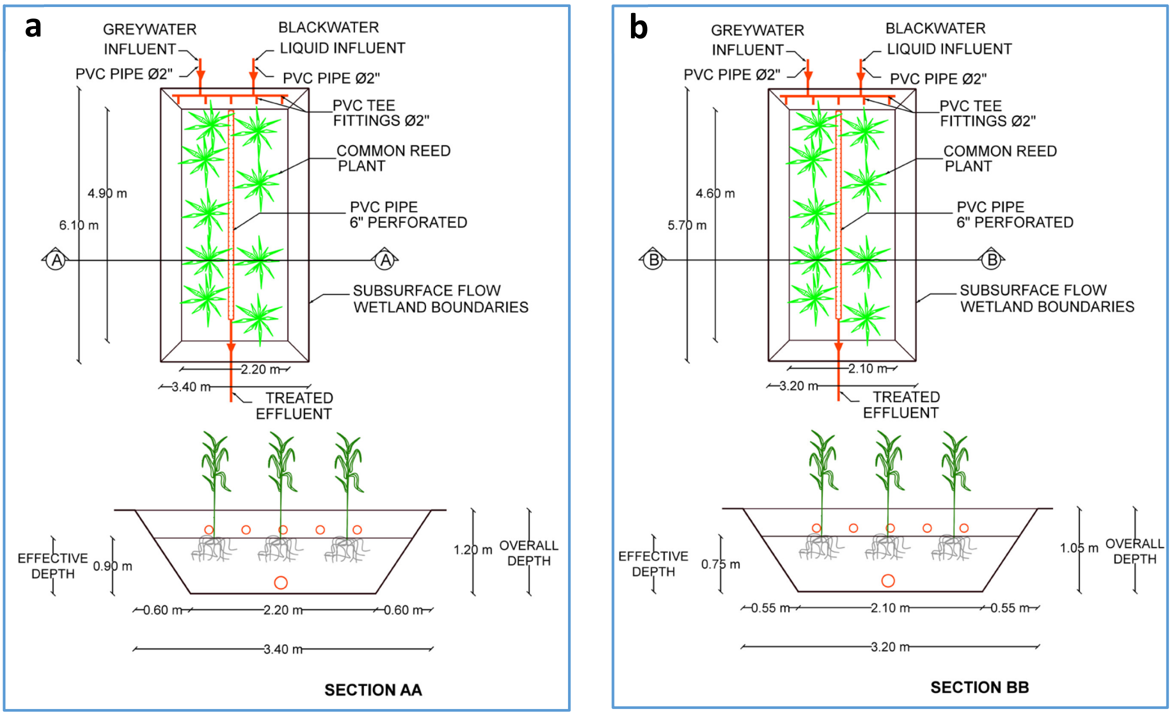


Figure 6-9: Sizes of SSF wetlands in (a) MEH prototype and (b) REH prototype. Design: Alnahhal, Samir, 2017.

Darcy's law that describes the flow pattern in porous media is used to determine the surface areas of the vegetation bed. However, Darcy's law is not applicable in the design of SSF wetlands when large or coarse rock gravel is used because of the turbulent flow that might occur. Nevertheless, the only accessible model for designing SSF wetlands is Darcy's law [Ree-93, p. 37] as defined in Eq. (6-7).

$$q = k_s I\ A \quad \text{.......} \quad (6\text{-}7)$$

Where:

q = flow per unit time, (m^3/d)

k_s = hydraulic conductivity of a unit area of the media perpendicular to the flow direction, ($m^3/m^2/d$)
A = cross-sectional area, perpendicular to the flow direction, (m^2)
I = hydraulic gradient of the surface water flowing in a bed $\Delta h/L$, (m/m)
Δh = head difference (m)

For a safety factor, Darcy's law can be used to check the hydraulic design of SSF wetlands. Darcy's law, with some recommended limits, including a hydraulic conductivity (k_s) which is 1/3 of the effective hydraulic conductivity and a hydraulic gradient ($\Delta h/L$) which is less than 10% of the maximum potential gradient in a bed, can be used to determine the flow (q) that can pass through the bed in a subsurface pattern. If this flow (q) is less than the total flow (Q_Δ) that is calculated in Eq. (6-2) clogging and surface flow are possible. In this case, the aspect ratio needs to be readjusted until Darcy's calculated flow is equal or greater the total flow [Ree-93].

In both modules, the design of the bed dimensions and aspect ratio that were obtained by the plug flow model (Eq. 6-6) were checked using Darcy's law with the previous recommended limits, as shown in Table 6-4. The water head difference (Δh) between the inlet and outlet is assumed to be 15 *cm*. Comparing the values of the hydraulic flow (q) in Table 6-3 and Table 6-4, the calculated flow by Darcy's law is much greater than the total flow (Q_Δ) in the SSF wetlands designed by the plug flow. This indicates that the bed dimensions and aspect ratio are acceptable and the bed is not susceptible to surface water flow.

Table 6-4: Determination of the flow that passes the wetland bed in the subsurface pattern using Darcy's flow.

Nr	Prototype module	Calculated length of the bed, (L)	Calculated width of the bed, (W)	Assumed depth of bed, (d)	Effective hydraulic conductivity (k_s)	Maximum potential hydraulic gradient, (I)	Cross-sectiona l area, (A)	Darcy's flow, (q)
		(m)	(m)	(m)	($m^3/m^2/day$)	(m/m)	(m^2)	(m^3/day)
		[1]	[2]	[3]	[4]	[5]=(Δh^*/L)	[6]=[2]* [3]	[7]=1/3*[4] * 0.1*[5]*[6]
1	MEH	5.3	2.6	0.90	100000	0.028	2.34	220.75
2	REH	4.9	2.4	0.75	100000	0.031	1.80	183.82

Materials specifications, components and construction details

The major concerns in the realization of SSF wetlands include the material specifications, components and construction details. The main components of the SSF wetlands are:

- Inlet structure
- Outlet structure

- Filtration media
- Vegetation type
- Bed Sealing

1) Inlet structure

The inlet of the SSF wetland allows the liquid to enter the wetland and to distribute this inflow along the width of the wetland bed. There are several forms of inlet, which depend on the type of the wetland, including: surface and subsurface manifolds, open trenches perpendicular to the flow direction, and single point weir boxes. The subsurface manifolds can have different features, including perforated pipes and valve outlet in the inlet. The use of a subsurface manifold can avoid surface flow, algae development, and clogging in the inlet zone. The main disadvantage of the subsurface manifolds is the difficult access for maintenance and future adjustments [Ree-93].

In the ROSS module, the SSF wetlands receive the liquid product from two subsurface manifold pipes, one for greywater and the second for blackwater liquid. Then both pipes are combined into one main pipe, which is connected to the manifold by means of a number of "tee" fittings that have a size equal to, or smaller than, the main pipe. A PVC pipe of diameter 4" (110 mm) is used as the main pipe, while PVC tee fittings of diameter 2" (50 mm) are used as the manifold inlet, as shown in Figure 6-10. During construction, the tee fittings should be laid at the same level. The author suggests covering the manifold tee fittings with a galvanized steel mesh of lesser size than that of the gravel in order to prevent any possible clogging.

Figure 6-10: Inlet structure of the SSF wetland in the REH prototype. Photo: Alnahhal, Samir, 2017.

2) Outlet structure

The outlet of the SSF wetland collects the liquid and allows the effluent to leave the wetland towards the storage and reuse equipment. Similar to the arrangement of the inlet, there are several forms of outlet equipment, including subsurface manifolds and gated structures, e.g., weir boxes. The perforated subsurface manifold is commonly used and it has various locations. In some cases, it is located below the bottom of the bed as a shallow trench to maintain maximum hydraulic gradient. However, in many cases, the manifold and outlet ports are located a little higher than the bed bottom. The perforated subsurface manifold is deemed as the most fixable and reliable outlet equipment, but its installation requires careful consideration because it is buried and inaccessible after construction [Ree-93].

In the ROSS module, a PVC pipe of diameter 6” (160 *mm*) is used as a perforated subsurface manifold. This pipe is installed 10 *cm* above the bed bottom and along the length of the bed. The end of the manifold pipe is closed from the inlet side, whilst the end of the outlet is connected to a PVC pipe of diameter 2” (50 *mm*) to collect the effluent towards the storage and reuse equipment. The level of the outlet pipe, i.e. the 2” (50 *mm*) pipe, is lower than the inlet manifold pipes by 15 *cm* as a head difference to maintain a hydraulic gradient for the flow in the wetland bed.

3) Filtration media

The filtration media is the key issue in the constructed wetlands because it affects the flow of liquid, and the overall performance. The characteristics of the filtration media include type, particle size, porosity, and hydraulic conductivity. The filtration media should be as uniform in size as possible. Very small particles, e.g., clay, are not recommended because they have low hydraulic conductivity that would cause surface flow. Very large particles are not suitable for plant root propagation and microorganism growth due to the reduced surface area per unit volume [UN-HABITAT-08]. It is highly recommended to use large size filtration media in the inlet and outlet zones to reduce clogging and resulting surface flow [Kop-07]. The recommended particle size ranges from 40-80 mm [USEPA-00].

In the ROSS module, a coarse rock of 80 mm particles is used in the inlet in order to improve the inflow and filtration speed, and to avoid any algae development and possible clogging. The effective depth of the vegetation bed (d) is also divided into two layers. The bottom layer that includes the perforated subsurface pipe is filled with a coarse rock gravel of 80-100 mm particle size in order to improve the drainage and effluent collection while avoiding any clogging. The top layer is filled with smaller coarse rock gravel of 40-80 mm particle size as shown in Figure 6-11.

The unsaturated zone above the effective depth is 30 *cm* thick. It is designed to prevent the surface water and allow the common reed to grow and spread in the vegetation bed. The backfill soil that is produced from the excavation of the bed can be reused for preparing and levelling the unsaturated zone.

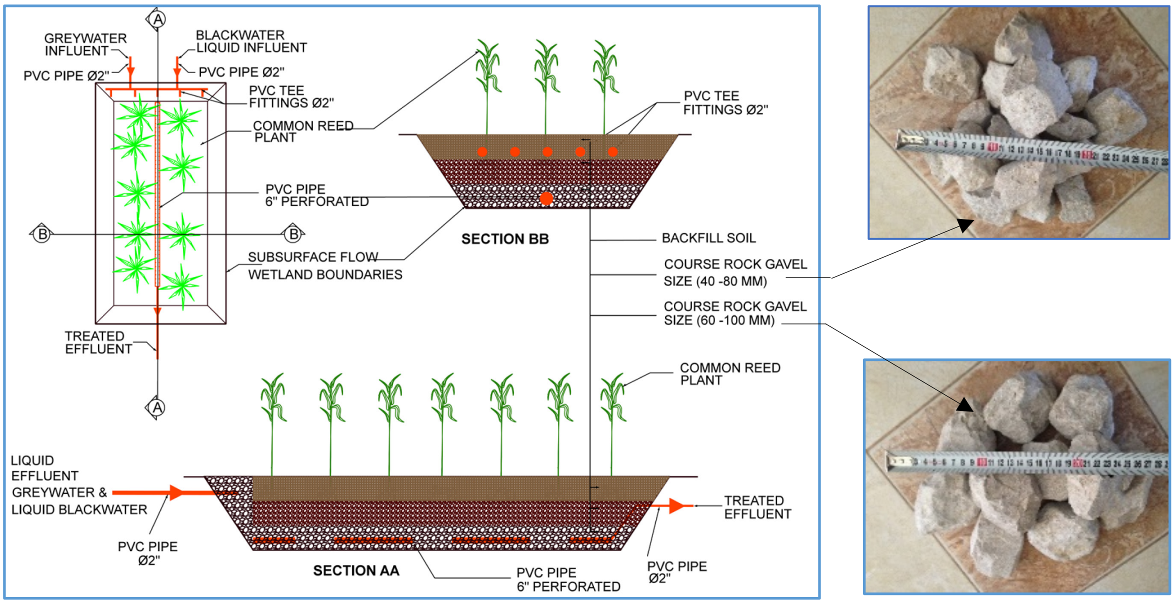


Figure 6-11: Coarse rock gravel sizes used as filtration media in the SSF wetland. Design and photo: Alnahhal, Samir, 2017.

4) Vegetation type

The emergent plant is one of the key issues for treatment of wastewater in CWs, besides the filtration media and available microorganisms [Woo-95]. There are several types of plants that can be used to plant the vegetation beds, including emergent plants, e.g., bulrush (*Scirpus*), common reed (*Phragmites Australis*), cattails (*Typhal*) [Ree-93], and water hyacinth plants, e.g., (*E. crassipes*) [Red-84]. Any of these plants is suitable for use in planting SSF wetlands. Nevertheless, selection of a plant type requires careful consideration regarding the treatment purposes and the climatic conditions [Ree-93].

The SSF wetlands that are planted with the common reed are very effective in removing organic matter and nitrogen from wastewater, although phosphorus removal is low compared to other CWs planted with other types of plant [Chr-08, p. 172]. The common reed can be found in several areas worldwide [Kad-09]. Common reed plants are widely used for planting the CWs in Europe because they offer several advantages, including the fact that they require low maintenance, they grow and spread faster than the bulrush, and their roots go deeper than cattails [Ree-93]. In the Gaza Strip, the common reed is also available and has been used in many CWs for the treatment of wastewater [Afi-13], [Afi-15], and for sludge dewatering [Nas-06].

At present, planting CWs with seedlings has improved growth compared to planting with rhizomes that need more time to grow and are significantly affected by the climatic conditions [Vym-02]. In the ROSS module, the seedlings of the common reed were used for planting the vegetation beds. The harvesting frequencies of the plant in the vegetation bed range from 3-5 times per year [Woo-95]. However, plant harvesting is not practiced in most cases [Vym-02], especially in Europe [Ree-93], because the plant cover can isolate the surface of the vegetation bed during cold weather [Vym-02]. In contrast, annual harvesting is practiced in the Gulf Coast of the United States (US). The harvesting of the plants would be useful to remove undesired weeds, especially during the growing period in the first few years of operation. However, routine annual harvesting of the entire bed is not recommended [Ree-93].

5) Bed sealing

Sealing of the vegetation beds is a fundamental component of CWs because it prevents the liquid from infiltrating below the CW beds. The infiltration of the liquid has negative impacts on groundwater quality and reduces the quantities of treated effluents. Plastic liners that are made of PVC, HDPE, or low density polyethylene (LDPE), with thickness ranges from 0.8 – 2.0 *mm* are mostly used for bed sealing [Vym-02]. Liners made of polypropylene (PPE) could also be used.

In the ROSS module, plastic liners made of PVC with a thickness of 2.0 *mm* are used. This type of liner has several advantages, including low cost, durability, and availability in local markets. It also has high resistance to the chemicals that may exist in the wastewater, and it is more flexible to seasonal variations in temperature. In most cases, a geotextile material is recommended to cover the main liner in order to protect it from any damages that might occur due to the sharp edges of the gravel filtration media [Vym-02]. In ROSS modules, since the geotextile material is relatively expensive and unavailable in the local markets of the Gaza Strip, another HDPE plastic sheet with thickness of 0.5 *mm* is used as the geotextile material and to cover the main liner as shown in Figure 6-12.

The efficiency and workability of the bed seal after lining was checked in both pilot modules by filling the effective depth of the bed with water. The water level was monitored and checked for 48 hours to ensure that no damages had occurred to the bed liner. The author found that adding this water was important not only for checking the liner workability but also for the growth of reed seedlings, especially when the module was under construction and in need of some time to start functioning. Moreover, the influent liquid requires some time to fill to the effective depth, especially in the larger modules or when septic tanks are used.

Figure 6-12: Bed sealing of the SSF wetland (a) labourers lay PVC plastic liner; (b) the second plastic liner as a geotextile material. Photo: Alnahhal, Samir, 2017.

6.2.3. Storage, reuse and disposal of treated liquid

In the ROSS module, flexible equipment for storage, reuse, and disposal of treated liquid from the SSF wetland is designed, developed and realized, as shown in Figure 6-13.

The storage, reuse and disposal equipment consists of two main parts. The first part is a storage and reuse tank which is used to store the treated liquid until a favourable time for it to be reused in irrigation. This storage and reuse tank is equipped with an electrical water pump to transport the effluent to the required place, specifically, where the land topography does not support the flow under gravity. However, most components of the ROSS module are developed and realized with a minimum use of electricity. This low use of energy is important for the areas which suffer from shortages and discontinuity in electrical supply, including the Gaza strip. This storage, reuse and disposal equipment could be made of any material that has the capability to store and contain liquids safely. In both prototypes, a P.E plastic tank of 1000 l capacity is used for the storage and reuse.

The second part is the disposal tank, which is connected to the storage and reuse tank. The disposal tank is designed, developed and realized to contain the excess treated liquid from the storage and reuse tank, before allowing this excess liquid to recharge the groundwater. The connection between the storage and reuse tank and the disposal tank is made from the top of the tanks to allow the storage equipment to store a certain quantity for reuse. In both prototypes, a P.E plastic tank of 1000 *l* capacity is used for the disposal and groundwater recharge. This tank is perforated from the bottom to facilitate the liquid infiltration into the subsoil. Below the disposal tank, a pit of 1000 *l* capacity (1 *m* length x 1.2 *m* width x 1 *m* depth) is excavated and filled with a coarse rock gravel of 80 *mm* particle size to ensure rapid infiltration of the excess liquid.

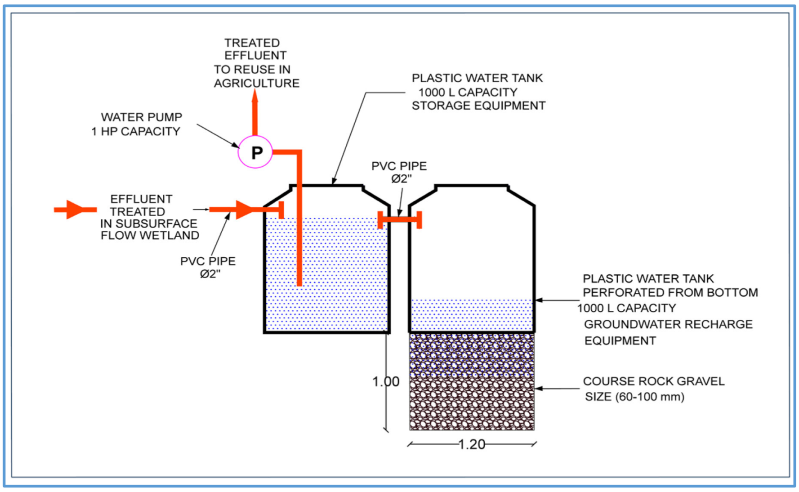


Figure 6-13: Storage, reuse, and disposal equipment in the ROSS module. Design and photo: Alnahhal, Samir, 2017.

6.2.4. Lactic acid fermentation for bio -solids waste treatment

Microbial processes, e.g., aerobic process, are an important element to maintain sustainability of any soil and are also responsible for production of the compost. Similar to normal soil, the aerobic process is expected to occur in TP soil and there is no evidence for occurrence of anaerobic processes, e.g., LAF, in the formation of TP soil [Gla-12], [Gla-13]. However [Fac-10] assumes the LAF process would strongly participate in the formation of TP soil [Fac-10].

With respect to the scope of this thesis, the LAF process was used for maintaining an initial stabilization of blackwater solids, reducing pathogen content, and improving the quality of the produced soil conditioner. Then, an aerobic composting process was followed for production of the Terra Preta-like substrate.

The LAF process can be started by storing bio-solid wastes with lactic acid bacteria, also called lactobacillus in air-tight container. The bacteria are added and mixed with the bio-solid wastes and other fermentable carbohydrates, e.g. fructose, or fruit sugars that are found in vegetables, fruit, and honey [Fac-13]. The lactic acid bacteria have the advantage of not being sensitive to oxygen (O_2), and can survive and grow in the presence of oxygen as well as in its absence [Gis-14]. However, a completely anaerobic condition is not preferred [Fac-13] because some fermentative bacteria need oxygen for their metabolic activities [Bat-98]. Therefore, in the pilot experiment, the fermentation tanks were kept airtight but not completely full with the mixture of blackwater solids, separated using SLS equipment, and charcoal activated in the nutrient adsorption tank. The addition of a carbon source, e.g., charcoal, for faecal sludge has a positive effect on mineralization of organic carbon and nitrogen, removal of offensive odour [Soe-13], and reduction of faecal pathogens [Soe-13], [Böt-13]. This is because the faecal sludge and blackwater solids have a limited carbon source for achieving a successful LAF process. Charcoal can also be added either before or after the LAF process [Spu-14]. In the pilot experiment, the charcoal was activated in the nutrient adsorption tank. Then it was added and mixed with the blackwater solids to start the LAF process.

The LAF process is possible for faecal sludge, but it is significantly influenced by its high water content, which should be reduced by separation of solids from liquid [Soe-13]. Therefore, the SLS equipment can provide a unique opportunity to reduce the water content of blackwater solids prior to the LAF process. Moreover, addition of charcoal can also reduce the water content. Approximately 10% of charcoal should be added to the organic materials as reported in many TPS projects, e.g., at a public toilet at Hamburg main station [Bet-13].

Therefore, the nutrient adsorption tank in the ROSS module was designed to contain 10% charcoal as shown in Table 6-5.

Addition of effective micro-organisms that contain a dominant population of lactic acid bacteria [Hig-94] to faecal sludge causes a decrease in the pH values because this bacteria can reproduce and produce acid. This process can result in a pH of 4 in a relatively short time [Jal-08], which is recommended for hygienisation of faecal materials [Sto-13]. In the pilot experiment, lactic acid bacteria was produced in the laboratory of the Islamic University. The lactic acid bacteria was isolated from milk yogurt. Using Lactobacillus selection agar base, the bacteria was reproduced in anaerobic jar for 24-48 hours at 37°C. The produced bacteria was added to the mixture of blackwater solids and charcoal. Then the mixture is kept in the fermentation tanks for 28 days as recommended by [Pra-13].

Table 6-5: Total volume of blackwater solids in the separation and storage period for both prototypes in Gaza.

Nr.	Prototype module name	Design number of users*	Total volume of blackwater solids (V_{Solids}) in separation and storage period *(litre)***	Percentage of charcoal *%*	Volume of Charcoal *** *(litre)*	Volume of Nutrient adsorption tank *(litre)*
		[1]	[2]	[3]	[4] = [2] * [3]	[5]
1	Mohammad El Hessi (MEH)	30	247	10	24.7	60
2	Ramadan El Hessi (REH)	21	173	10	17.3	60

* Actual Number of users x 25%
** Total volume of blackwater solids per 60 days as calculated in Table 6-1
*** Charcoal volume l per 60 days

6.2.5. Composting for bio-solids waste treatment and reuse

Vermicomposting is a crucial step in TPS [Fac-10] and production of the Terra Preta-like substrate [Pra-13], [Pra-15], which can also be carried out at the household level [Fac-13].

Through this thesis, a small-scale composting experiment has been implemented for the blackwater solids for 85 days after 28 days of LAF process. The VC process was replaced by a two-phase composting process, mainly thermal and normal composting, for the decomposition and hygienisation of faecal materials. The reasons for this were:

- The VC process has challenging requirements that are not easily handled by untrained persons, including provision of a suitable living condition for the earthworms through adjusting (1) the moisture content between 80-90% for rapid growth of worms [Gry-04]; (2) operation temperature from 15 to 20°C and below 30°C [Sha-06]; (3) alkalinity of the bio-solid wastes mixture between pH 4-9 [Gry-04]; (4) compost heap setup arranged in layers by a mixture of other bulking agents, e.g., VC product, or other materials, e.g., soil [Yad-10]; and (4) the carbon to nitrogen (C:N) ratio of 70:30 [Itc-13], because faecal material has been found to be an unsuitable environment for earthworms due to the high content of ammonia [Fac-10]. The C:N ratio can be increased by the addition of bulking agents. These can be wood chips and straw, or any carbon rich material, e.g., corn cobs [Itc-13].

- VC with involvement of earthworms, e.g., *Eisenia fetida*, was not effective to eliminate the faecal pathogens indicator, Salmonella spp., in faecal materials which were mixed with charcoal and other organic solid waste, e.g., food residues and plant cuttings [Sto-13].
- Adding a mixture of soil and other bulking substrates would provide a suitable environment for earthworms [Yad-11]. However, with respect to the scope of this thesis, it will influence the physical, chemical and biological characteristics of the compost produced from blackwater solids. Hence, it would be difficult to evaluate the characteristics of compost produced from blackwater solids and charcoal.
- It was difficult to secure a sufficient quantity of earthworms since these were not available in the local markets of the Gaza Strip.

Similar to the VC process, an aerobic decomposition for bio-solid wastes can be carried out either in a closed composting chamber, or in an open-air composting compartment in the form of heaps or windrows [Gis-14]. A composting heap was prepared, which undergoes thermal composting, and no worms were added. For the hygienisation purpose and based on [Soe-13] suggestions, the thermal composting was carried out for two weeks by covering the composting heap with plastic sheet and keeping the heap without water addition or aeration. This was followed by normal composting for 10 weeks, with periodic addition of water, and turning over every 3-5 days for aeration to maintain the aerobic condition. The composting process was implemented in the grounds of a local nongovernmental organisation, “Palestinian Environmental Friends” (PEF) laboratory.

6.3. Monitoring, results, and discussion

6.3.1. Monitoring protocol

A monitoring protocol was prepared through this thesis to provide a standardized and effective way to monitor the workability and efficiency of the ROSS module through observing and inspecting the changes in the characteristics and quality of the module output products, including the treated water effluent and the Terra Preta-like substrate.

Influent liquid wastes and treated effluent

The monitoring protocol includes physical, chemical, biological, and health concern parameters for the blackwater and greywater influents and treated effluent. Locations of sampling points (SPs) are presented in Figure 6-14. The frequency of sample collection and laboratory testing, testing procedure, and name of the instruments used are shown in Table 6-6. The parameters were selected based on the PSI recommended guidelines as shown in Annex (II.I), which are also compatible with the WHO recommendations for monitoring the reuse of wastewater [Aye-85], [WHO-06], and the capacities of local technical laboratories in the Gaza Strip.

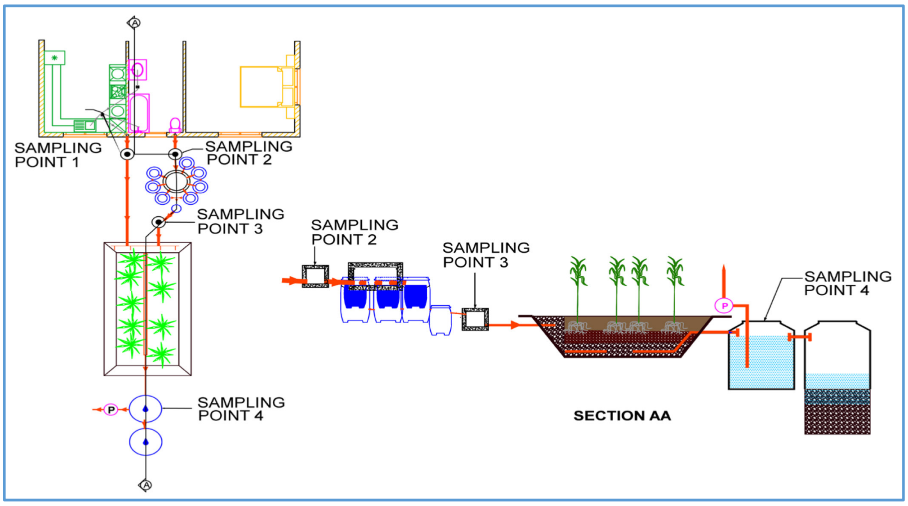


Figure 6-14: The sampling points on the ROSS modules. Design: Alnahhal, Samir, 2017.

The locations of the SPs were arranged to be before and after the main processes and equipment, e.g., SLS and SSF wetland. Four SPs were provided:

- SP (1) represents the blackwater that flows from households towards the SLS equipment. This point gives a reference for the physical, chemical and biological characteristics of raw blackwater.

Table 6-6: Testing parameters for the characteristics of the liquid waste influents and treated effluent.

Nr.	Testing parameters	Symbol	unit	Testing Frequency	Procedure	Name of instrument
1	**Physical Properties**					
1.1	Temperature	T	°C	twice	Probe method	Digital thermometer
1.2	Electrical conductivity	EC	dS/m (or) mmho/cm	twice	Probe method	EC meter
1.3	Total Solids	TS	mg/l	twice	Evaporation method and instrument	
1.4	Total dissolved solids	TDS	mg/l	twice	Probe method	TDS meter
1.5	Imhoff (settleable solids)	SS	ml/l	twice	Imhoff method	Imhoff cone
2	**Chemical Properties**					
2.1	Acidity/Basicity	pH	-	twice	Probe method	Turbidity meter
2.2	Chloride	Cl-	me/l	twice	Titration method	Digital titration unit
2.3	Ammonia	NH_3	mg/l	twice	Kjeldahl method	Kjeldahl, distillation and titration unit
2.4	Nitrate	NO_3	mg/l	twice	colorimetric method	UV-spectrophotometer
2.5	Total kjeldahl nitrogen	TKN	mg/l	twice	Kjeldahl method	Kjeldahl, digestion, distillation and titration unit
2.6	Phosphorous	PO_4	mg/l	twice	Digestion method	Kjeldahl, digestion unit and spectrophotometer
2.7	Total organic matter	TOM	mg/l	twice	Loss on ignition method and instrument	
3	**Biological properties**					
3.1	Chemical oxygen demand	COD	mg/l	twice	Closed reflux method	Spectrophotometer & COD reactor
3.2	Biological oxygen demand	BOD_5	mg/l	twice	Oxitop method	Oxitop
4	**Health concern**					
4.1	Faecal coliform	FC	MPN/g or FCu/100ml	twice	Filtration technique	Incubator

- SP (2) represents the greywater that flows from households towards the SSF wetland. This point gives a reference for physical, chemical and biological characteristics of greywater.
- SP (3) represents the blackwater liquid that flows from SLS equipment and the nutrient adsorption equipment towards the SSF wetland. This point gives a reference for the chemical and biological removal efficiency of the SLS equipment and nutrients adsorption equipment.
- Sampling point (4) represents the treated effluent from the SSF wetland. This point gives an indication for the level of water purification and treatment efficiency of the ROSS module, and to what extent the treated effluent can be reused in agriculture.

The first-round samples were collected from the four SP locations after two months of operating the prototype, whilst the second-round samples were collected after five months of operation. Each sample in the first round and second round was combined from three grab samples into one composite sample. The period between each grab sample was from 2.5-3 hours. The use of composite samples and two-round sampling was due to the large number of samples and the high expense of the chemical reagents. Moreover, the collected samples were tested and analysed in the laboratories of Environment and Rural Research Centre, Islamic University of Gaza, Gaza strip.

Terra Preta-like substrate

The protocol for monitoring the Terra Preta-like substrate that is produced from bio-solid waste and charcoal via the LAF and the composting processes included some physical, chemical, and biological parameters based on the WHO recommendations [WHO-06] and the available capacities of local technical laboratories in the Gaza Strip. The testing procedure and the name of the testing instrument are presented in Table 6-7.

Table 6-7: Testing parameters for the characteristics of the Terra Preta-like substrate.

Nr.	Testing parameters	Symbol	unit	Procedure	Name of instrument
1	**Physical Properties**				
1.1	Density	ρ	kg/m3 or g/l	Weighing method	
1.2	Electrical conductivity	EC	dS/m (or) mmho/cm	Electrical conductivity method and instrument	
1.3	Moisture content	MC	%	Drying and weighing	Drying oven
2	**Chemical Properties and plant nutrients**				
2.1	Acidity/Basicity	pH	-	Glass electrode method	
2.2	Chloride	Cl-	ppm	Titration method	Digital titration unit
2.3	Ammonia	NH_3	(mg/kg dry weight)	Kjeldahl method	Kjeldahl, distillation and titration unit
2.4	Total kjeldahl nitrogen	TKN	(mg/kg dry weight)	Kjeldahl method	Kjeldahl, digestion, distillation and titration unit
2.5	Phosphorous as P_2O_5	P_2O_5	(mg/kg dry weight)	Olsen’s method (Ascorbic Acid Method	
2.6	Potassium as (K_2O)	K2O	(mg/kg dry weight)	Flame Photometric Method	
2.7	Organic matter	OM	%	Loss on ignition method	
2.8	Lead	Pb	mg/kg	Inductively Coupled Plasma (ICP) method - ICP-AA-X -ray	
2.19	Cadmium	Cd	mg/kg		

Nr.	Testing parameters	Symbol	unit	Procedure	Name of instrument
3	**Health concern**				
3.1	Faecal coliform	FC	MPN/g	Filtration technique	Incubator
3.2	Ascaris Lumbricoides		MPN/g	Microscopic	

The round one sample was taken from the Terra Preta-like substrate produced from the blackwater solids and charcoal due to the large number of samples and the high expense of the chemical reagents. One composite sample was combined from five grab samples collected from different locations of the compost heap.

6.3.2. Quality analysis for liquid waste influent and treated water effluent

This section discusses the quality of the liquid waste influent and treated water effluent flowing through the ROSS module in the REH prototype. Based on the monitoring protocol, some field measurements and laboratory analysis for the physical, chemical, and biological parameters are made and presented in Annex (III). Both prototypes (MEH and REH) were designed, developed, and implemented based on the same concept as specified in Chapter 6, Section 6.2. The MEH slightly differs from the REH prototype in the total flow that passes through the module according to the number of people in each family. Both modules were realized in the same area and both households have similar living conditions and water use. For monitoring purposes, one prototype (REH) was selected to be representative for the ROSS module due to the large number of samples and the high costs of the reagents.

Field measurements

The field measurements of blackwater and greywater influents and treated water effluent include temperature, electrical conductivity, and acidity/basicity.

The temperature of wastewater is commonly higher than that of drinkable water. The mean annual temperatures ranges from 10°C to 25°C throughout the year [Smd-09] with an average of 16°C, depending on the geographical location. The temperature of water is a very important parameter due to its effect on chemical reactions in the treatment process [Rab-10], reaction rates, aquatic life, and suitability of water for beneficial uses [Tch-03].

As shown in Figure 6-15 (a), the temperature of blackwater is slightly greater than that of greywater. The temperature of blackwater and greywater influents is slightly decreased from an average of 25.5°C and 24.6°C, respectively, to about 22.8°C for the treated water effluent.

The results showed that the average pH for blackwater and greywater influents and treated effluents were 7.5, 7.4, and 7.5, respectively, as shown in Figure 6-15 (b).

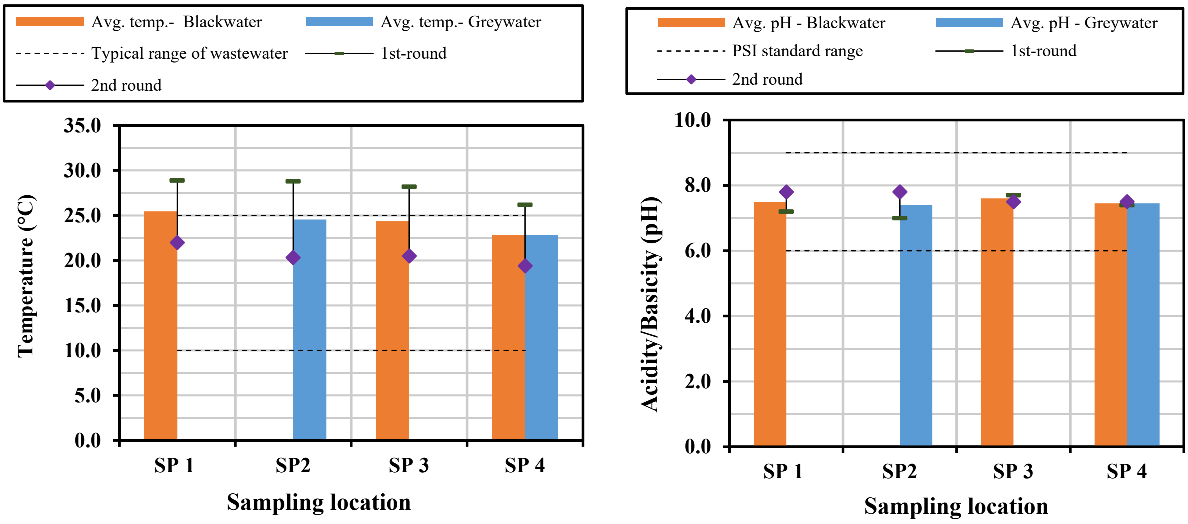


Figure 6-15: Field measurements of blackwater and greywater at the various treatment locations for (a) average temperature, ° C; (b) acidity/basicity, pH.

The variation in the pH values along the ROSS module was insignificant, particularly after the SLS equipment in location SP3, since solids separated in the filter bags were stored for a short period of 2 months. Therefore, no complete anaerobic digestion may have occurred. The anaerobic digestion causes a significant drop in the pH values. The pH value of the treated water effluent falls within the accepted range of pH 6-9 based on the PSI standard [PSI-00]. Moreover, the user has not noticed offensive odour during removal of the full filter bags and the installation of replacement ones.

The electrical conductivity (EC) is one of the most widely used indicators for the total ionized constituents of water [Pes-92]. It is also a useful parameter for assessing the concentration of solids present in wastewater. The EC is defined as a measure of the wastewater's ability to convey electric current [Tch-02]. The unit of EC is deciSiemen per meter (*dS/m*) in SI Units (equivalent to 1 *mmho/cm*) [Pes-92], which equals 1000 microSeimen per centimetre (*µS/cm)*. The EC of domestic wastewater commonly ranges from 50 to 1500 *µS/cm* [WEF-08].

The results indicate that the blackwater has greater EC values than the greywater due to the high concentration of solids contained in the blackwater as shown in Table 6-8. The average value of EC for the treated water was 1805.0 *µS/cm,* which falls within the "slight to moderate" restriction band for reuse in agriculture. This band ranges from 700 to 3000 *µS/cm* based on FAO guideline. With restrictions in the slight to moderate range, more care in the selection of the crop type is required if full yield potential is to be achieved [Aye-85].

Table 6-8: Field measurements of electrical conductivity for influents and effluent at the various treatment locations.

Sampling location	Electrical conductivity		
	1st-round sampling	2nd- round sampling	Average
	(µS/cm)	*(µS/cm)*	*(µS/cm)*
SP1	>2000	1795	1795.0
SP2	1055	1430	1242.5
SP3	>2000	1860	1860.0
SP4	1840	1770	1805.0

Solid removal

Total solids (TS) is a measure of all suspended and dissolved solids in a sample of liquid, including dissolved salts, e.g., sodium chloride (NaCl), and solid particles, e.g., silt and plankton. The TS is a useful parameter to assess the reuse potential of treated water from wastewater. The TS is also used to determine the suitable type of treatment processes and is usually expressed as mass per unit volume, most commonly *mg/l* or *ppm*. The TS concentration of typical domestic wastewater ranges from weak to medium to strong as 350, 700, and 1200 *mg/l*, respectively [UN -85]. Table 6-9 shows that the TS concentrations of influents, and treated water effluent were very strong and much exceeded the typical concentrations. This strong concentration of TS can be due to the low daily use of water that ranges from 50 to 70 l/c.d. based on the user's experience. Other reasons for high TS concentrations include the high amounts of dissolved solids in the water supply in the Gaza Strip, and the pre-separation of blackwater from greywater.

The total suspended solids includes the inorganic (fixed) suspended solids and the organic (volatile) suspended solids [Spe-07]. The TSS is a useful parameter to assess the quality of wastewater after the different treatment processes. The TSS also gives a measure of the turbidity and microbial contamination of the wastewater, which can interfere with the effectiveness of disinfection. The PSI allowable range of TSS concentration for reuse of treated water in agriculture and groundwater recharge is 30-60 *mg/l* [PSI-00].

Table 6-9: Total solids concentrations of blackwater and greywater at the various treatment locations.

Sampling location	Total solids (TS)		
	1st-round sampling	2nd- round sampling	Average
	(mg/l)	*(mg/l)*	*(mg/l)*
SP1	4364	4037	4200.5
SP2	2744	2619	2681.5
SP3	3401	3340	3370.5
SP4	2811	2758	2784.5

As shown in Figure 6-16 (a), the TSS removal efficiency is highly affected by TSS concentration in the influent [Koł-15]. The reduction of TSS concentrations in the treated water effluent was 92.5% and 95.8% in the first and second round results, respectively, as shown in Figure 6-16 (a). The SLS equipment contributed to removal on average 60% of TSS total removal percentage. The average removal efficiency is expected to be greater than 94.1% as the TSS load in the greywater was not considered in the calculations. These calculations require hydraulic flow measurements for both blackwater and greywater.

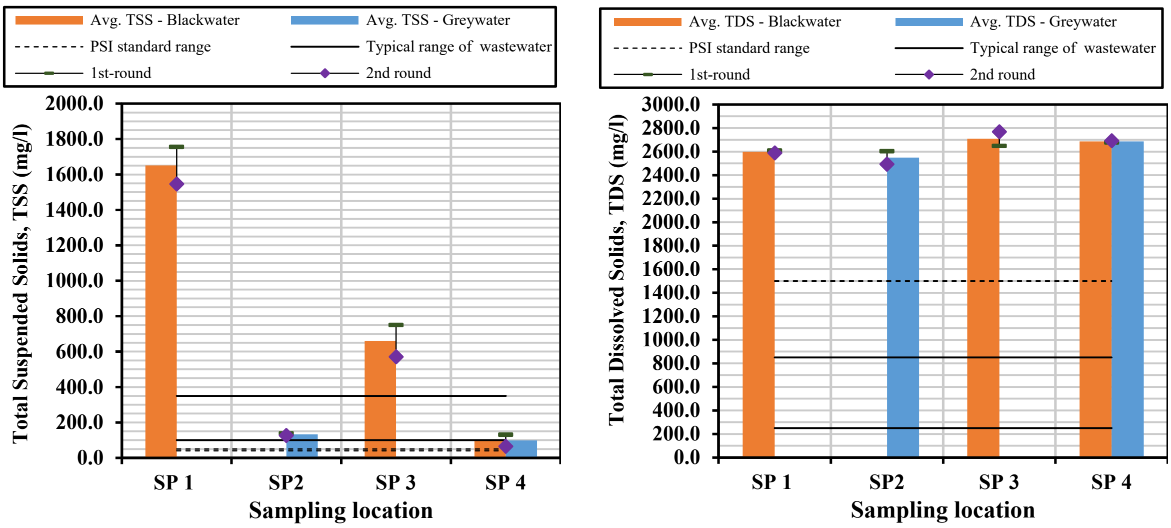


Figure 6-16: Laboratory analysis of blackwater and greywater at the various treatment locations for (a) total suspended solids, TSS; (b) total dissolved solids, TDS.

The flow measurements were not achieved through this thesis because of lack of measurement devices in the local markets of the Gaza Strip. Although TSS concentrations in the influents of both blackwater and greywater were much higher than that of typical wastewater that range from 100-350 *mg/l* [UN -85], the performance of the SLS equipment was high as separation through filtration occurred. The TSS removal efficiency of most conventional pre-treatment equipment, e.g., septic tanks, is about 50% [Til-14] and can range from 40 to 60% [EAWAG-16]. Based on [Kir-11], the TSS removal in septic tanks depends on wastewater concentration, hydraulic retention time and degree of cleanliness. The TSS removal was 77% ±10% with a clean septic tank and three days retention time. After two months, TSS removal decreased to 53% ±22%. The TSS removal was also reduced to 45% ±40% for one day of retention time [Kir-11]. On the contrary, the SLS equipment has an acceptable efficiency for removing high concentrations of TSS with only a few minutes retention time. Moreover, in the SLS equipment, TSS removal increases as the TSS concentration reduces.

The TSS removal efficiency of the SSF wetland was slightly reduced, which is expected due to the high concentrations of TSS in the influents of blackwater and greywater. However, the performance of the module in removing TSS is acceptable as the average removal efficiency reached more than 94%. Findings from previous studies as presented in Table 3-2 showed that TSS removal ranges from 50% to 90% for the modules that use pre-treatment equipment and SSF wetlands, depending on the type and configuration of treatment and TSS load in the influent liquids. However, the average TSS in the treated water effluent was slightly greater than the PSI recommended guideline that ranges from 40-50 mg/l for different uses [PSI-00].

Total dissolved solids is a measure of the amount of material dissolved in the wastewater, including carbonate, bicarbonate, chloride, phosphate, nitrate, magnesium, calcium, sulphate, sodium, organic ions, and other ions. Many of these materials may not be deemed as pollutants. Similar to electrical conductivity, the TDS is a useful parameter for estimating the concentration of solids present in wastewater [Tch-03] and is usually expressed as mass per unit volume, most commonly *mg/l* or *ppm,* similar to TS units.

The results showed that the concentrations of TDS in blackwater and greywater were 2599 and 2493 *mg/l*, respectively, with slightly greater TDS in blackwater compared to greywater as shown in Figure 6-16 (b). The TDS removal was not significant as the ROSS module is designed for removing suspended solids rather than dissolved solids. Moreover, the high concentration of TDS in both greywater and blackwater is strongly associated with the quality of the water supply. These findings are compatible with other findings by [Yad-11], [Afi-13] as the TDS reduction in constructed wetlands is not significant [DeB-00]. Moreover, the increase in the TDS concentration in the effluent compared to the influent can be explained due to using different sources for the water supply from municipal wells and agricultural wells.

This occurs because the supply of municipal water is not continuous due to irregular supply of electrical power that the Gaza Strip has suffered from over the last decade. Therefore, different waters that mixed inside both the SLS equipment and the SSF wetlands could cause the increase in concentrations of TDS.

In most parts of the Gaza Strip, high TDS concentrations results from the problem of seawater intrusion phenomenon that deteriorates the quality of the water supply. This phenomenon is mainly caused by the over-pumping of water from groundwater wells. This water is also not balanced by any natural replenishment from rainfall or by anthropogenic replenishment from reuse or recharge of treated wastewater [Ais-13]. The groundwater in the Gaza Strip is the predominant source for water supply. Recent studies have indicated that this groundwater is polluted by high salinity as the TDS concentration in about 49% of groundwater wells exceeds the WHO standard limit of 1000 *mg/l* [May-10]. The TDS concentration in groundwater is also rapidly increasing with time [Hee-05]. The TDS concentration ranges from 692-4036 *mg/l* with an average of 2274 *mg/l* in Rafah Governorates [Abb-13], where the ROSS module is implemented.

As shown in Figure 6-16 (b), the concentration of TDS in the treated water was 2686.5 *mg/l* exceeding the PSI recommend value of 1500 *mg/l* for various reuse applications [PSI-00], as shown in Annex (II.I). Use of treated water that has high TDS concentrations may result in soil and cropping problems or lower yields. Therefore, it is recommended that before using this water in a large scale, pilot farming experiments should be conducted to determine the effect of such water on the soil, and crops [Aye-85].

Settleable solids (SS) are those solids that will settle to the bottom of a cone shaped container within one hour, called an Imhoff cone. The unit of settleable solids is *ml/l* [Spe-07]. Settleable solids are a common parameter for evaluating the quality of water and wastewater [Hnd-06]. The typical range of SS in domestic wastewater is 5 – 20 *mg/l* [Rab-10].

The results revealed that the average reductions of SS concentration of the treated water effluent was less than 0.5 *ml/l* with 97.6% average removal as shown in Figure 6-17. After the SLS equipment and nutrient adsorption tank the SS concentration was reduced from 20.6 to 8.8 *ml/l* with 57.3% removal efficiency. The SSF wetland contributed to reduce the SS concentration by 40.3% from 8.8 to < 0.5 *ml/l*. This removal percent is also expected to be greater as the SS load from greywater was not considered in the calculations due to lack of hydraulic flow measurements for both blackwater and greywater.

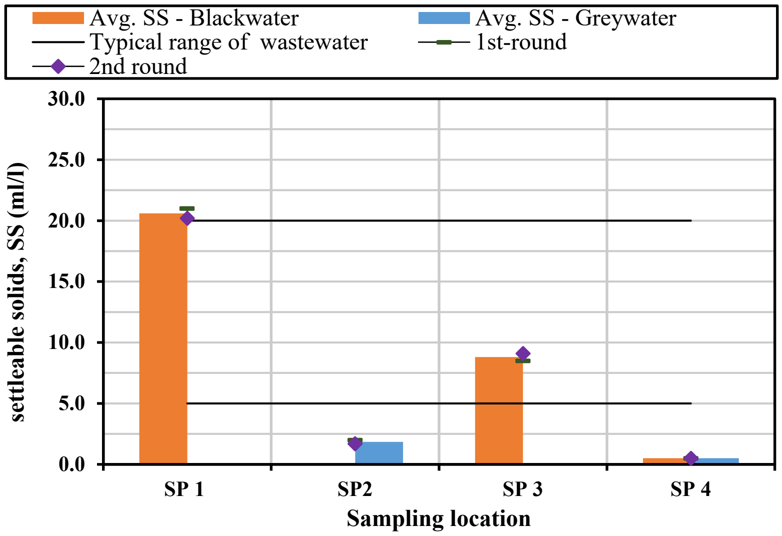


Figure 6-17: Average concentration of settleable solids, SS of blackwater and greywater at the various treatment locations.

Nitrogen removal

Naturally, nitrogen exists in several forms. The basic nitrogen forms of concern to wastewater treatment are total nitrogen (TAN), total Kjeldahl nitrogen (TKN), which includes organic nitrogen (Org-N) and ammonia (NH_3), nitrate (NO_3) and nitrite (NO_2). Their concentrations are mostly reported in *mg/l*. The forms of nitrogen that are present in wastewater depend upon the treatment condition, treatment stages and availability of oxygen [Tch-03].

1) Ammonia

In the aquatic environment, the vast majority of organic nitrogen is immediately hydrolysed into ammonia (NH_3 and NH_4), depending on the pH value of that liquid. When the pH value is within the range of neutral or acidity, i.e., below pH 8, about 95% of NH_3 is converted into ammonium ions (NH_4^+) [Cri-06], which is typically called ammonia, not ammonium. However, when the pH value increases over pH 11, the NH_4 is totally converted into NH_3 and the majority of nitrogen is in the form of NH_3 [Spe-07]. The typical range of ammonia in wastewater is 12-50 *mg/l* for weak and strong concentrations [Hen-10]

The concentrations of ammonia (NH_4 + NH_3) were analysed in the laboratory for the samples collected from the various treatment locations SP1 to SP4, and the concentrations of ammonia are presented in terms of the chemically equivalent element nitrogen, i.e., NH_4- N, as shown in Figure 6-18.

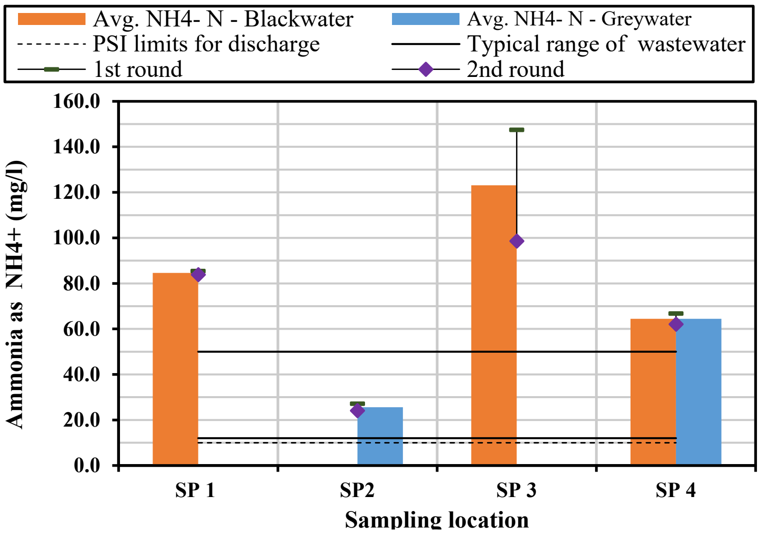


Figure 6-18: Average Ammonia in blackwater and greywater at the various treatment locations.

The results revealed that the average concentration of ammonia in the treated water effluent was 64.4 *mg/l*. In the SLS equipment this was increased from 84.6 mg/l to 123.1 *mg/l* due to the hydrolysis of organic nitrogen or the ammonification process which converts the organic nitrogen into ammonia in anaerobic conditions. The anaerobic condition occurs due to limited oxygen that can promote the aerobic condition and allows the nitrification process to oxidize the ammonia into nitrates by means of the nitrifying bacteria. The reasons for limited oxygen could be the air tightness of the SLS equipment and the fact that no aeration equipment was installed. The ammonia in the ionic form is not toxic but in the gaseous form it becomes toxic for aquatic life. Therefore, there is no restricted limit for reuse in irrigation as it is considered as a nutrient source for plants and commonly the pH of treated water is within the range of neutral or acidic. However, for disposal in bodies of water and groundwater recharge, the recommended limit of ammonia should not exceeds 10 mg/l based on PSI [PSI-00].

2) Total Kjeldahl nitrogen

The Kjeldahl nitrogen (TKN) is made up of ammonia (NH_4 and NH_3) and organic nitrogen (Org-N). The source of organic nitrogen is due to the deamination reactions during the metabolism of organic materials in wastewater [Cri-06]. The results showed that the average concentrations of TKN in blackwater and greywater influents were 194.5 and 35 *mg/l*, respectively, and in the treated effluent this was reduced to 93.5 *mg/l* as shown in Figure 6-19.

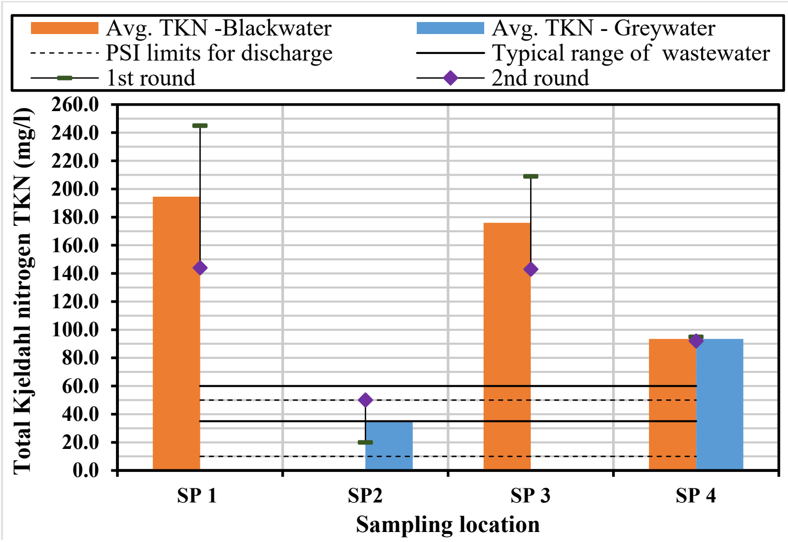


Figure 6-19: Average total Kjeldahl nitrogen in blackwater and greywater at the various treatment locations.

The average removal of TKN was 51.9 %; the actual removal is expected to be higher as the TKN load from the greywater was not taken into consideration due to the lack of hydraulic flow measurements. These findings are similar to those achieved by [Afi-13] in a similar module implemented in the Gaza Strip. The removal of TKN is mostly dependent on oxygen availability. In the SLS equipment, as anaerobic condition is maintained, the TKN was slightly reduced on average to 9.5%. The SSF wetlands contributed to the reduction in TKN by 42.4% on average. Commonly, oxygen is limited in the SSF wetland and this could be the reason for the low efficiency of TKN removal [Ree-93], particularly in the early operational phase as the roots of the plants are still young and have not yet established their own roots within the filtration media. The TKN removal is expected to improve with time in SSF wetlands.

3) Nitrate

Nitrate (NO_3) is the most oxidized form of nitrogen found in wastewater. For groundwater recharge, nitrate is important because of its serious effect on infants [Tch-03]. The PSI recommended limits of nitrate in the treated water effluent for groundwater recharge state that the concentration should not exceed 15 *mg/l*, and for reuse in agricultural applications should not be more than 50 *mg/l* [PSI-00].

The nitrate (NO3) was analysed for blackwater influent and treated water effluents and the nitrate is reported in the chemically equivalent element nitrogen called nitrate-nitrogen (NO3-N). The concentration of NO3-N in the treated water effluent was 0.4 mg/l, which is below the PSI standard limits [PSI-00]. Insignificant increase in the nitrate concentration in the effluent was expected due to limited capacity of the SSF wetland to transfer oxygen, since the roots of the plant are still young in the early phase of operation.

Phosphorus Removal

Phosphorous (P) is one of the major nutrients that plants need to grow. However, discharging wastewater with high a concentration of phosphorus into the bodies of water causes eutrophication and water quality problems that require purification at high cost. Typical domestic wastewaters may contain from 6 to 20 *mg/l* of total phosphorous [UN -85]. The phosphorus removal from wastewater could be achieved in either a chemical process called phosphorus precipitation or a biological process by bacteria. In the constructed wetlands, phosphorus is hardly removed, depending on the capacity of the filtration media to adsorb, bind or precipitate the incoming phosphorous [Ari-05].

As shown in Figure 6-20, the average concentration of phosphorus in the treated water effluent was 6 *mg/l* with 75.8% removal efficiency, which is expected to be higher as the P load from greywater was not considered due to the lack of hydraulic flow measurements.

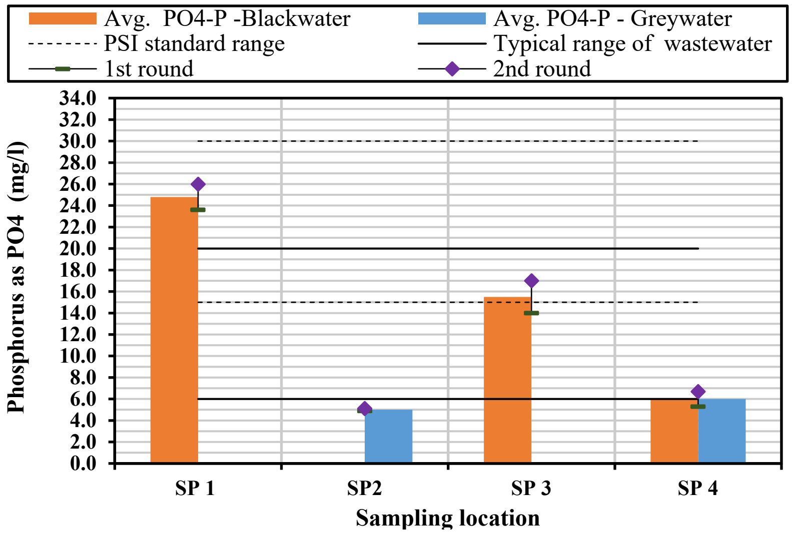


Figure 6-20: Average phosphorus in blackwater and greywater at the various treatment locations.

The SLS equipment and nutrient adsorption tank contributed to remove 37.5% of P concentration from the total percent, while the SSF wetland contributed 38.3% to the total removal. The PSI recommended limits ranges from 15 to 30 mg/l [PSI-00].

Organic material removal

Wastewater is a mixture of organic material and aggregates, with an average size range from 1 *nm* to 1 *mm*. Organic material is the major pollutant in domestic wastewater, which is a heterogeneous mixture of molecules, ranging from simple to complex substances [Rkt-71]. Therefore, the removal of organic material from wastewater is essential to meet the acceptable quality standards for either safe disposal or reuse. Traditionally, organic material can be measured by biological oxygen demand (BOD) and chemical oxygen demand (COD). The BOD test measures the oxygen used for oxidation of part of the organic matter based on the principle that if sufficient oxygen is available, aerobic biological decomposition, i.e., stabilization of organic waste by microorganisms, will continue until all organic wastes are consumed. BOD analysis is very useful in the control of wastewater effluent, and is expressed in *mg/l*. The BOD test is also known as "BOD_5", which measures dissolved oxygen (DO) at the beginning and end of a five-day period in which the sample is incubated in dark conditions at 20°C. The change in DO concentration over five days yields the oxygen demand needed for respiration by the aerobic biological microorganisms in the sample. The COD test determines the amount of organic pollutants found in a liquid, making COD a useful indicator for water and wastewater quality. COD measures the amount of oxygen consumed per litre of solution, which is expressed in *mg/l*. COD measurements are essential for designing the various treatment processes and mass balances in wastewater treatment [Hez-08].

As presented in Figure 6-21, the average removal of BOD_5 was 78.9%, a reduction from 1275 to 269 *mg/l*. The total removal is expected to be greater as the BOD_5 load from the greywater was not taken into account due to the lack of hydraulic flow measurements. Moreover, the improvement in BOD_5 removal is expected to increase with time as the common reed plant requires time to grow and to establish its own roots.

The SLS equipment and nutrient adsorption tank contributed to reduce BOD_5 from 1250 to 695 *mg/l* with average removal of 45.5%. The SLS equipment shows encouraging efficiency in removing high concentrations of BOD_5. The conventional pre-treatment equipment, e.g., septic tanks, has 30-50% removal efficiency of BOD_5 for typical domestic wastewater with low BOD_5 concentration. Considering BOD_5 from blackwater only, the SSF wetland contributed to the removal of 33.4% of BOD_5 reducing concentrations from 695 to 269 *mg/l.* Hence, the total removal is expected to be greater as the average concentration of BOD in the greywater was 368.5 *mg/l*.

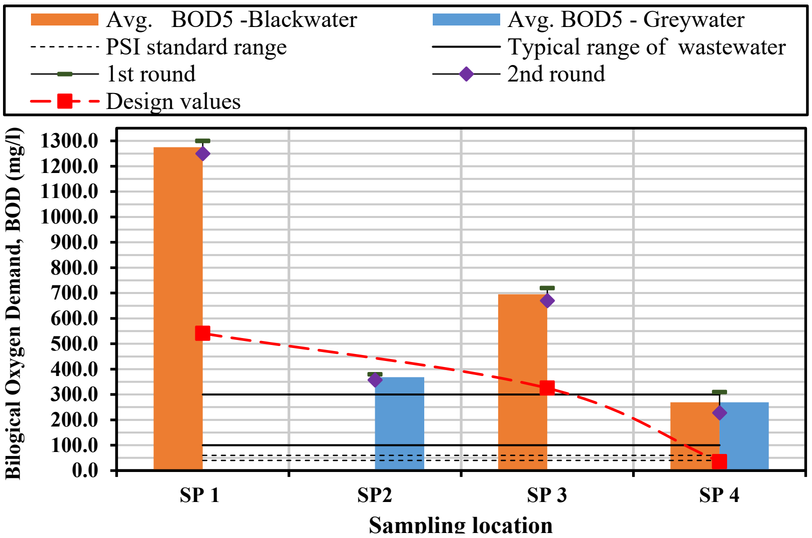


Figure 6-21: Average biological oxygen demand, BOD5 in blackwater and greywater at the various treatment locations.

The BOD_5 concentrations were greater than the design values of 541 and 35 *mg/l* in the influent and effluent, respectively. In addition, the BOD concentration in the influents were much higher than the typical range for domestic wastewater (100-300 *mg/l*) [UN -85]. The PSI recommended guideline for BOD_5 concentrations in the treated water effluent ranges from 40 to 60 *mg/l* [PSI-00]. The high level of BOD would limit the reuse of the effluent in irrigation, particularly for the vegetables. Moreover, the author recommends following safety measures, e.g., hand washing and hand gloves, during any intended use to prevent direct contact with the user. In addition, redesign of the module, particularly the SSF wetland, and measure of the actual BOD_5 concentration in the raw wastewater before starting the design in the future are recommended.

As shown in Figure 6-22, the average concentration of COD in the treated water effluent was reduced by 86.1% from 4781 to 665 *mg/l*. The total reduction is expected to be greater as the COD load from the greywater was not taken into consideration due to the lack of hydraulic flow measurements for both blackwater and greywater. These concentrations of COD in the blackwater are much greater than the typical range for domestic wastewater (450-700 *mg/l*) [UN -85].

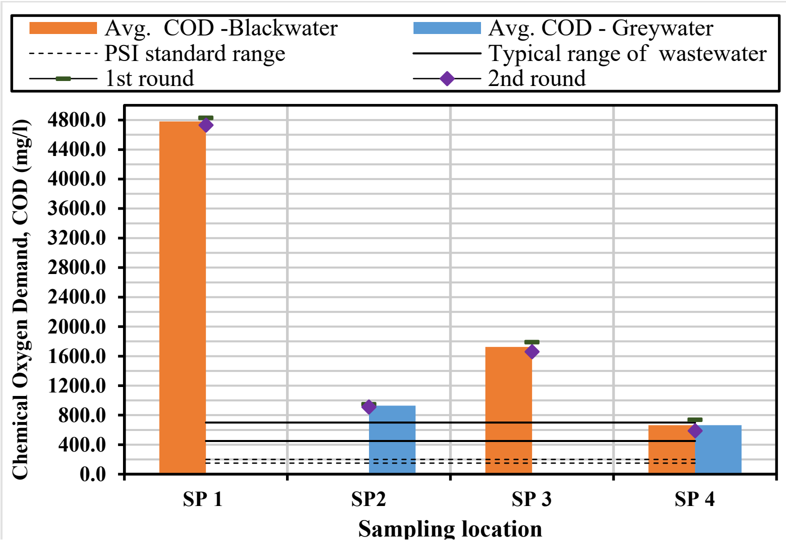


Figure 6-22: Average chemical oxygen demand, COD in blackwater and greywater at the various treatment locations.

The SLS equipment and nutrient adsorption tank contributed to the removal of on average 63.9% of COD from 4781 to 1726 *mg/l*, while the SSF wetland removed 22.2%, considering the COD load from blackwater only. Similar to the BOD, the COD removal efficiency in the SSF wetland is expected to improve with time. The PSI recommended guideline for COD concentrations in the treated water effluent ranges from 150 to 200 *mg/l* [PSI-00].

Pathogen removal

Pathogen removal is a crucial process in the treatment of wastewater because pathogens pose severe problems to human health and the environment. Faecal coliform (FC) is one of the health concern parameters that can be used as an indicator for pathogenic contamination in the treated water effluent [Ree-93], [Tch-03]. The removal efficiencies in wetlands vary depending on operation, maintenance, and climatic conditions [Til-14], as well as organic loading rates. Typically, the minimum and maximum concentration range of FC in domestic wastewater is 340,000 to 49,000,000 “Most Probable Number” *MPN/100ml* [USEPA-86].

The result investigated that the removal level of FC reach around two log units with an average removal of 99.40% from 635,000 to 3,590 *Cfu/100ml*, as shown in Figure 6-23. The total FC removal is expected to be greater since the load from greywater was not taken into consideration due to lack of hydraulic flow measurement for both blackwater and greywater.

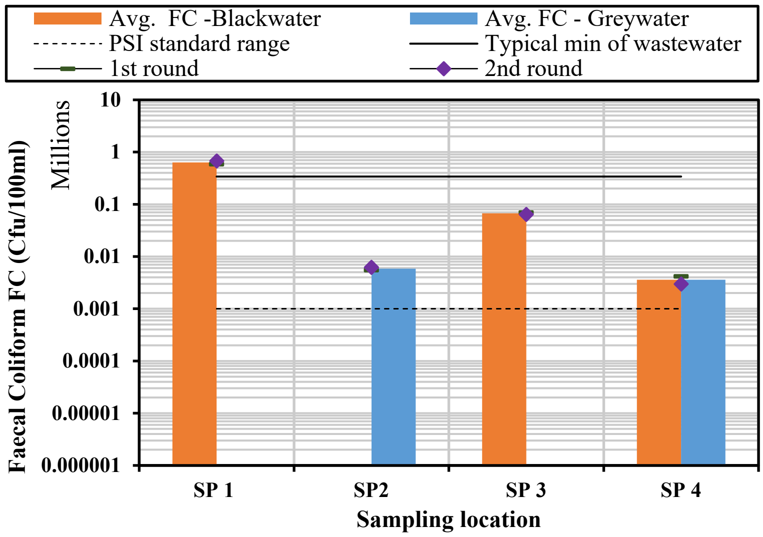


Figure 6-23: Concentration of Faecal coliform, FC in blackwater and greywater at the various treatment locations

In the SLS equipment, one log unit of FC was removed, which is similar to that can be achieved in well-designed and maintained septic tanks [Til-14]. In the SFF wetland, an additional one log unit was removed. Generally, in SFF wetlands, one to two log units of FC are typically removed [Ree-93] and removal can reach up to three log units, when iron-rich sand and HRT of one week are used [WHO-06]. Four log units removal of FC was also reported in [Afi-13]. It is expected that FC removal will be improved in the SSF wetland with time as the plant roots can grow and their capacity to transfer oxygen can be maintained. Hence, more biodiversity and increased populations of micro-organizes in the root zone are to be expected. The removal level of FC and quality of the treated effluent is suitable for reuse in irrigation based on the PSI recommended guideline [PSI-00].

6.3.3. Quality analysis for the Terra Preta-like substrate

This section discusses the quality of the Terra Preta-like substrate produced from blackwater solids and charcoal via lactic acid fermentation and aerobic composting. The quality of produced substrate was investigated based on the monitoring protocol through collecting a composite sample and conducting laboratory tests for some physical, chemical, and biological parameters. The results are compared with typical and maximum range of compost produced from faecal materials, as presented in Table 6-10.

Table 6-10: Testing parameters for the characteristics of the Terra Preta-like substrate.

Nr.	Testing parameters	Unit	Measured value	Typical / maximum range	Reference
1	**Physical Properties**				
1.1	Density	kg/m^3 (wet weight)	576	500-700	[USCC-16]
1.2	Electrical conductivity	µS/cm	978	1-10000	[USCC-16]
1.3	Moisture content	%	53.4	40-50	[USCC-16]
2	**Chemical Properties and plant nutrients**				
2.1	Acidity/Basicity	-	7.5	6-8	
2.2	Chloride	mg/kg (dry weight)	1,738	Any content	[BMJV-12]
2.3	Ammonia	(mg/kg dry weight)	987	-	
2.5	Total kjeldahl nitrogen	(mg/kg dry weight)	10,860	Total Nitrogen (1.0-1.5)	[BMJV-12]
2.6	Phosphorous as P_2O_5	(mg/kg dry weight)	12,940	0.5	[BMJV-12]
2.7	Potassium as (K_2O)	(mg/kg dry weight)	28	75	[BMJV-12]
2.8	Organic matter	% (dry weight)	74.93	-	
	Organic carbon	% (dry weight)	43.56	-	
2.9	Lead	mg/kg	0.02	100-150	[BMJV-12]
2.10	Cadmium	mg/kg	0.11	1-2.5	[BMJV-12]
3	**Health concern**				
3.1	Faecal coliform	MPN/g	Nil	1000	[USEPA-93]
3.2	Ascaris Lumbricoides Ova	MPN/g	+ve	-	

Physical properties

1) Bulk density

The bulk density is a measure of the mass of material within a given volume of the substrate. The bulk density has a key role in achieving the optimum efficiency of the composting process. It also influences mechanical properties of the substrate, including porosity, strength, and ability of compaction [Mhe-05]. The bulk density of the sampled substrate was 576 kg/m^3. The optimal bulk density of compost ranges from 500 to 700 kg/m^3. A substrate with lower density than this is likely too dry, or contains too large particles to compost properly. Higher density means the substrate is likely too wet, or has particles that are too small to allow circulation of oxygen [Pau-09].

2) Electrical Conductivity

Electrical Conductivity (EC) is a measure of dissolved salts present in the liquid, soil, or compost. The electrical conductivity of sampled substrate was 978 *µS/cm*. Most composts have an electrical conductivity of between 1000 to 10,000 *µS/cm*. This considerable variation in the conductivity levels depends on feed stocks and processing mechanisms. When EC ranges from 750 to 2000 *µS/cm*, the substrate can be directly used for small plants and seeding. Whereas, conductivity levels above 2000 *µS/cm* would likely require dilution by irrigation [Dar-16]. [Fac-10] found the electrical conductivity of Terra Preta-like substrate produced experiments from blackwater solids and charcoal in laboratory and pilot scale ranged from 1700-3030 *µS/cm*.

3) Moisture content

Moisture content (MC) is a measure of the quantity of water present in a compost or substrate. The moisture content of the sampled substrate was 53.4%. The preferred moisture content of compost is 40-50%. Below 35% moisture, the substrate is overly dry or can be dusty and needs wetting. Above 55% moisture, the substrate is a very wet and it can be heavy and clumpy, making its use more difficult and its transportation more expensive [USCC-16].

Chemical properties

1) Acidity/Basicity

The pH is a measure of acidity or basicity of a liquid, soil, or compost. The pH of the sampled substrate was 7.5. Most composts have a pH range of between 6 to 8 [USCC-16]. Within this range, adjustment of pH before reuse in farming is not required. Below pH 5.5, the activity of soil microorganisms and availability of nutrients are sharply reduced [Bra-74]. However, the averaged pH value of Terra Preta soil is 5.4 as measured in 29 different sites [Snl-80].

2) Nutrient content

Nitrogen (N), Phosphorus (P, usually expressed as P_2O_5), and Potassium (K, usually expressed as K_2O) are the main three nutrients for the plants. Commonly, these nutrients are measured and expressed on a dry weight basis, in the form of a percentage (%). Knowing the contents of these nutrients help making correct decisions regarding the addition of supplemental fertilization elements. The nutrient content of compost products vary widely [USCC-16], depending on the feed stocks and production processes.

Generally, the nitrogen content can be measured by performing either Kjeldahl (TKN) test or combustion method by CHN analyser. The nitrogen content of the sampled substrate is measured by TKN test and found to be 1.09% dry weigh.

The phosphorus as (P_2O_5) of the sampled substrate was 12,940 *mg/kg* dry weight. The potassium content was 28 *mg/kg* of dry weight. The total nutrient content of sampled substrate could reach 2.373 % of dry weight, which is acceptable compared to the typical range of good compost of faecal sludge and to that of different Terra Preta soils as shown in Table 6-11.

Table 6-11: Nutrient contents of sampled substrate, good faecal sludge compost, and Terra Preta soil.

Element	Sampled substrate	Good Compost of faecal sludge	Terra Preta Soil		
		[Hor-84]	[Cos-09]	*[Snl-80]*	*[Som-66]*
Nitrogen	1.09%	1.0-1.5%	-	0.05-0.46%	0.06-0.44%
Phosphorus as P_2O_5	1.294%	1.2-2.0%	0.98-1.52%	2.6-3,150 mg/kg	65-660 mg/kg
Potassium as K_2O	0.00%	0.2%	0.31-0.76%	2.9-234 mg/kg	23.4-128.7 mg/kg

3) Organic matter

Organic matter content is the measure of carbon in the soil, compost, or substrate, usually expresses as a percentage of dry weight. Organic matter is needed for all soils and plays a key role in soil structure, nutrient availability, water holding capacity, and microbiological activity. Knowing the content of organic matter helps estimating the age and physical properties of the compost or substrate, as well as determining the application rates on certain crops, i.e., the quantity of organic matter needed on a per acre or hectare basis. There is no ideal value for organic matter content of compost and may vary widely, ranging from 30 to 70% of dry weight [USCC-16]. If organic matter is 30% by weight, which is common in compost. The remaining 70% is ash and minerals. The content of organic matter in the sampled substrate was 74.93% of dry weight.

4) Heavy metals

Heavy or trace metals are elements which have a potential for toxicity to humans, animals, or plants when present in high concentrations than regulated standards either in the water or food. Therefore, regulations for governing the heavy metal content in composts were set by the legal entities. Heavy metals include arsenic, cadmium, chromium, copper, lead, mercury, molybdenum nickel, selenium, and zinc. Many of these elements are needed by plants for normal growth, although in certain limits. Therefore, measuring the concentration of these elements, is important to investigate the quality of produced composts or soil conditioners [USCC-16].

Due to the high expenses of testing heavy metals and limited laboratory equipment in the Gaza strip, lead (Pb) and cadmium (Cd) were selected as indicators for the presence of heavy metals in the sampled substrate. The concentrations of lead and cadmium measured in sampled substrate were 0.015, and 0.105 *mg/kg* respectively, which is lower than maximum limits based on different standards as listed in Table 6-12.

Table 6-12: Maximum concentrations of heavy metal for compost products.

Element	German Standard	United States of America standard	Australian Guidelines
	[BMJV-12]	[Brn-00]	[EPA-13].
	mg/kg	*mg/kg*	*mg/kg*
Lead (Pb)	100-150	150	150
Cadmium (Cd)	1.0-2.5	4.0	1.0

5) Health concerns

Faecal coliform and Ascaris Lumbricoides Ova were measured as indicators for pathogenic bacteria and parasites in the sampled substrate. The results showed the sampled substrate was free of faecal coliform. The removal of faecal coliform could be occurred due to reduction of pH less than 4 in the lactic acid fermentation process, or the thermal composting, where the temperature might reach more than 55°C. Hence, lactic acid fermentation followed by thermal composting and then normal aerobic composting may be an effective option for eliminating pathogens. Based on U.S. Environmental Protection Agency (EPA), part 503 – Class "A" pathogen requirements for land application of sewage sludge, the faecal coliform density should be less than 1000 "most probable number" MPN per gram of total dry solids (1000 MPN/g TS)[USEPA-93].

The Ascaris Ova was noticed in the sampled substrate. This would limit the use of produced substrate for planting the vegetables. Safety measures e.g., hand washing and hand gloves, should be taking into consideration during the use of this substrate. However, lactic acid fermentation and aerobic composting of faecal sludge material is effective for eliminating Ascaris ova [Ste-78], particularly when effective microorganisms are added [Fac-13] [Itc-13].

7. Summary and outlook

Water and sanitation are fundamental to well-being and human development. Access to improved sanitation and water supply is recognized as a human right. Sanitation has a significant influence on human health through the spread of faecal-borne diseases and on the environment through polluting a large amount of fresh water. Human mortality is also closely linked to poor sanitation. Emerging countries are facing a clearly manifesting crisis in sanitation, which is of special concern to the international community and the United Nations. Worldwide, current progress on sanitation is not sufficient to meet the target of Millennium Development Goals and the sanitation crisis is expanding. This is due to the rapid growth of population, enhancement of living standards, and global urbanization, which must tackle open defecation besides improved coverage of sanitation.

Although conventional centralized management of wastewater has made a revolution in protecting human health, it is not an economic option for poor communities in emerging countries because it requires high investment costs, significant amounts of resources and skilled labour for operation and maintenance. As a water-based sanitation, the conventional centralized approach consumes high water quantities, which presents a big challenge, particularly in water-stressed areas. Additionally, based on the working principle of such approaches, drinking water, nutrients, and potential energy are wasted due to at-source mixing of all wastewater streams. Consequently, the economic and environmental sustainability of this approach may still be questionable.

From another point of view, the conventional decentralized approach is not an appropriate solution for the sanitation crisis with increasing population growth and growing urbanisation. This approach is often not capable of protecting the environment and avoiding contamination of groundwater, although it releases pressure on drinking water sources.

Globally, less attention has been paid toward adequate management of wastewater, including all processes in the sanitation chain, namely, containment, collection and storage, transport, treatment, and safe disposal and reuse. Adequate management of wastewater can lead to effective recovery and reuse of resources contained in wastewater, which can yield multiple benefits for future water and food security. Therefore, a paradigm shift in water and sanitation management is now essential based on the concept of sustainable sanitation. Consequently, one of the possible approaches to cope with this sanitation crisis is a resource-oriented approach that considers not only protection of human health and the environment, but also closes the loops on water and nutrients.

This thesis investigates the workability and efficiency of a sanitation module for on-site management of domestic wastewater and solid organic wastes at a household level based on the concept of resource oriented sanitation. This resource oriented, sustainable sanitation module was designed, developed, realized, and monitored for two prototypes implemented in the southern governorate of the Gaza Strip. The main features of the module are that it is low-cost; low-tech; and easy to implement, operate, and maintain; as well as culturally adoptable for communities in semi-urban and rural areas in emerging countries. For managing the liquid waste, including greywater and blackwater, the greywater stream is first separated from the blackwater stream. The blackwater is allowed to flow toward the solid-liquid separation equipment that was designed, developed, and realized for the first time through this thesis. Through this equipment, the blackwater solids are separated and stored in filter bags in a manner that is safe, hygienic, and socially acceptable, while the liquid flows toward a nutrient adsorption tank using locally made charcoal. The effluent then flows to the subsurface flow wetlands for additional treatment before reuse in irrigation and/or recharge of groundwater. The blackwater solids and activated charcoal were treated and converted to a Terra Preta-like substrate based on the concept of Terra Preta sanitation that mainly consists of lactic acid fermentation and the vermicomposting process. However, the vermicomposting process was replaced by thermal and normal composting processes to overcome some drawbacks of vermicomposting and for hygienisation purposes for the produced substrate. The realization of the resource oriented, sustainable sanitation module was accomplished with consideration for the locally available resources and materials, and with less requirements for energy, e.g., electricity.

To monitor the workability and the treatment efficiency of this module, field measurements and laboratory analyses for physical, chemical and biological parameters of the treated water effluent and the produced Terra Preta-like substrate were performed. These were performed for one prototype due to the large number of samples, and local availability and high expenses of chemical reagents needed for performing the laboratory tests. The monitoring results revealed that the module efficiency for removing total suspended solids, chemical and biological oxygen demands, and pathogenic indicator measured by faecal coliform were 94.1%, 86.1%, 78.9%, and 99.4%, respectively. The treatment efficiency is expected to improve with time, particularly with regard to the vegetation plants of the subsurface flow wetland that require time to grow and develop their roots to improve the transfer of oxygen and achieve effective treatment. Moreover, the treatment efficiency of the module is also expected to be higher than the presented results because the loads from the greywater were not considered in the calculations, since this requires hydraulic flow measurements for both greywater and blackwater. The lack of measurement devices in the Gaza Strip hindered these measurements in this thesis. The treated effluent was characterized by high dissolved solids compared to the recommended values of Palestinian standards because these solids were present in the water supply in high concentrations, and the module was designed for reducing suspended solids and hygienisation purposes rather than desalination purposes. However, the quality of the treated water effluent may be suitable for reuse in irrigation.

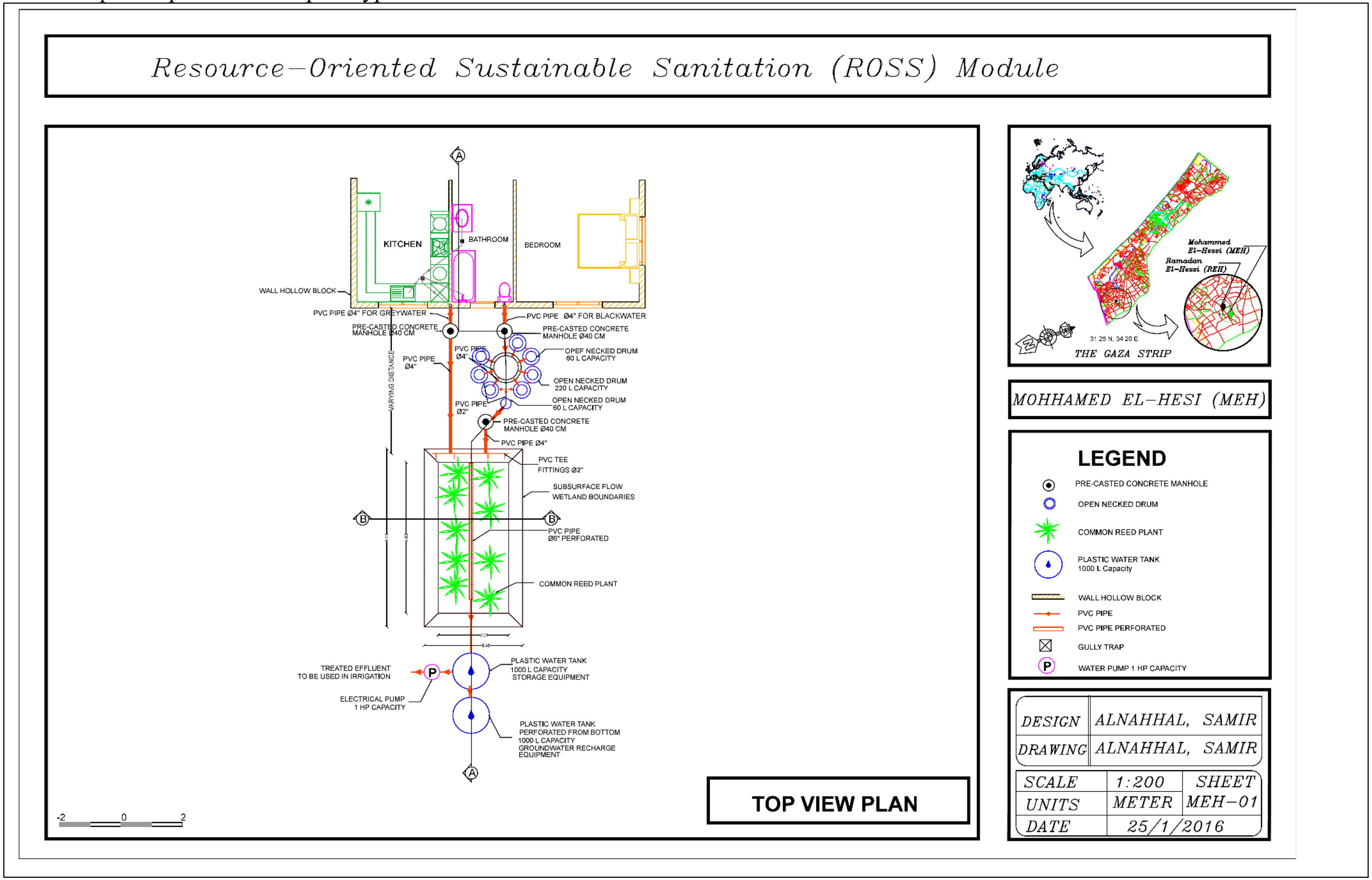
The finding for the sampled Terra preta-like substrate produced by lactic acid fermentation followed by thermal and normal composting processes demonstrated that the substrate has acceptable properties compared to good compost products from faecal materials. The physical properties of sampled substrate include bulk density of 576 kg/m^3, electrical conductivity of 978 $\mu d/cm$, and moisture content of 53.4%. The chemical properties as represented by the pH, total nutrient content (N,P,K), and organic matter were 7.5, 2.373%, and 74.93%, respectively. The heavy metals of the sampled substrate as represented by lead and cadmium concentrations were below maximum restricted limits, which are stated in the German and United States standards. The sampled substrate was free from faecal coliform as a pathogenic indicator however, Ascaris Ova was noticed in the sampled substrate. This may limit the use of the substrate for some plants, e.g., vegetables. Moreover, following good hygiene practices, e.g., hand washing and wearing hand gloves, are highly recommended when using such products.

For further investigation of the workability and efficiency of the ROSS module, it is recommended to perform other testing rounds and to consider further quality indication parameters in different periods of operation. It is also recommended to compare the results with other international standard limits and guidelines. Pilot experiments are needed to investigate the response of different types of plants irrigated by the treated effluent. Hydraulic flow measurements for both streams of blackwater and greywater are required for making the material (nutrients) flow analyses. Replication in different areas, either with same or different climates, requires redesign of the module and wastewater characterization before starting the implementation.

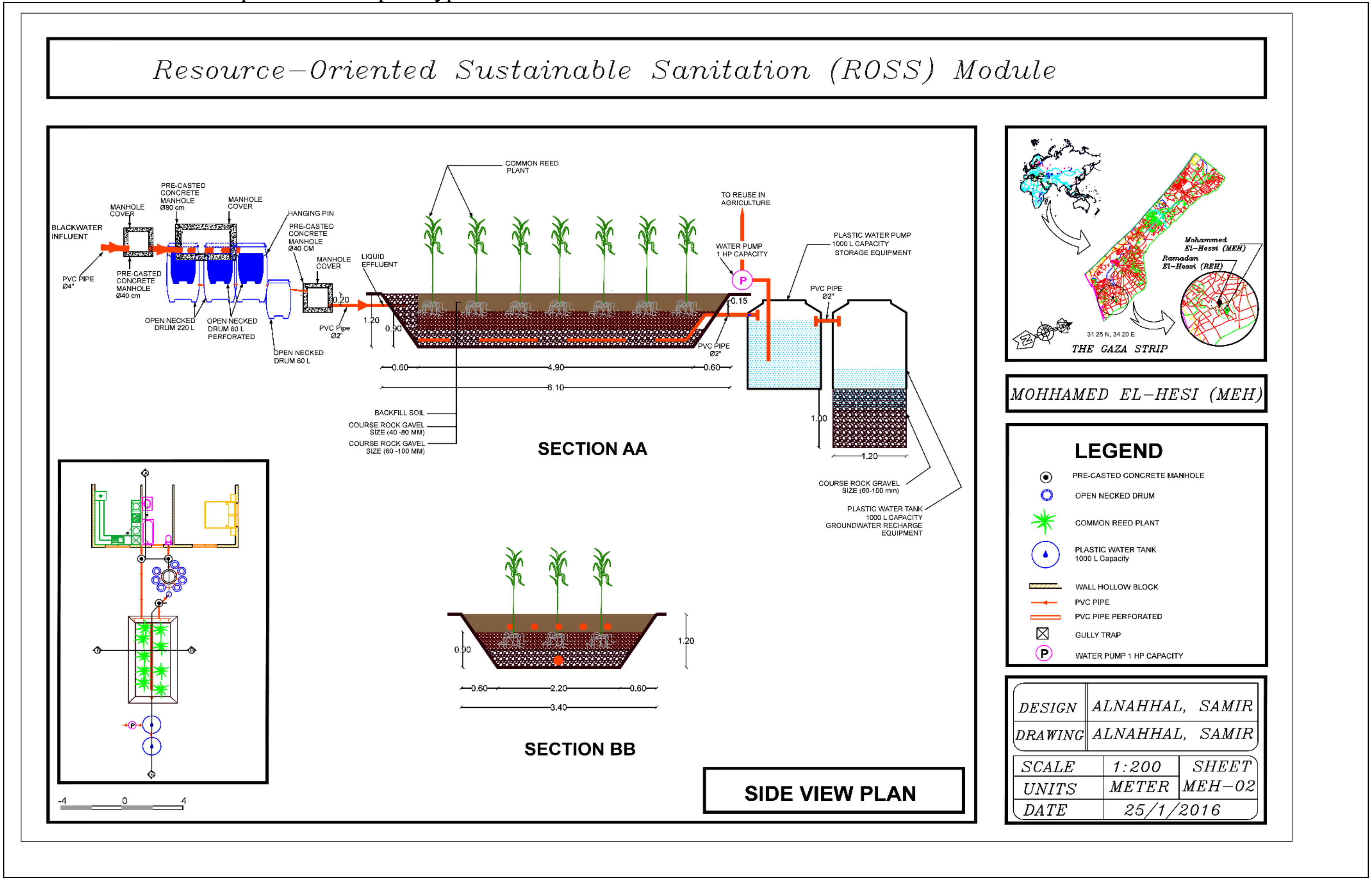
Annexes

I. Schematic design of ROSS module

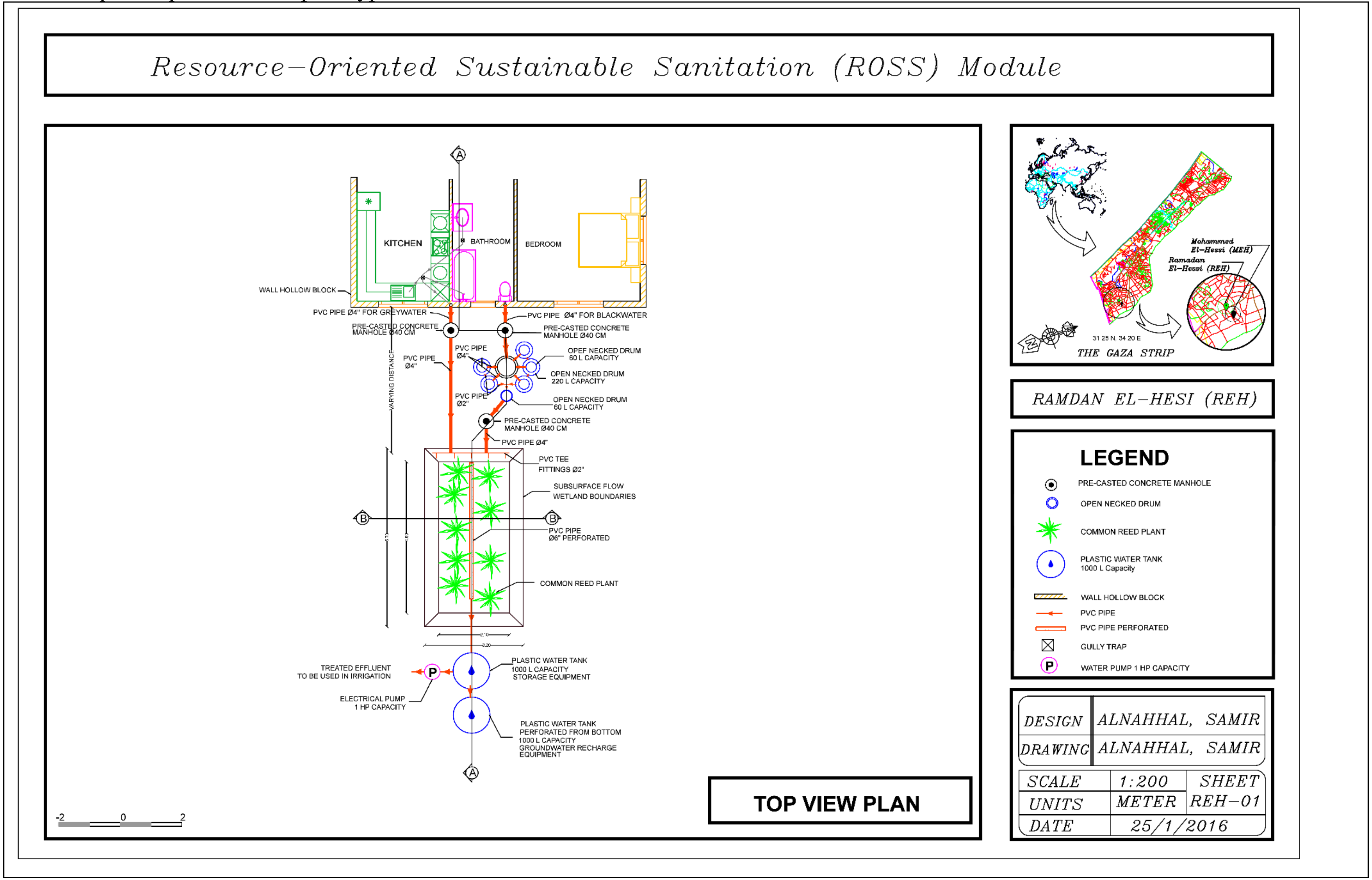
I.I. Top view plan for MEH prototype



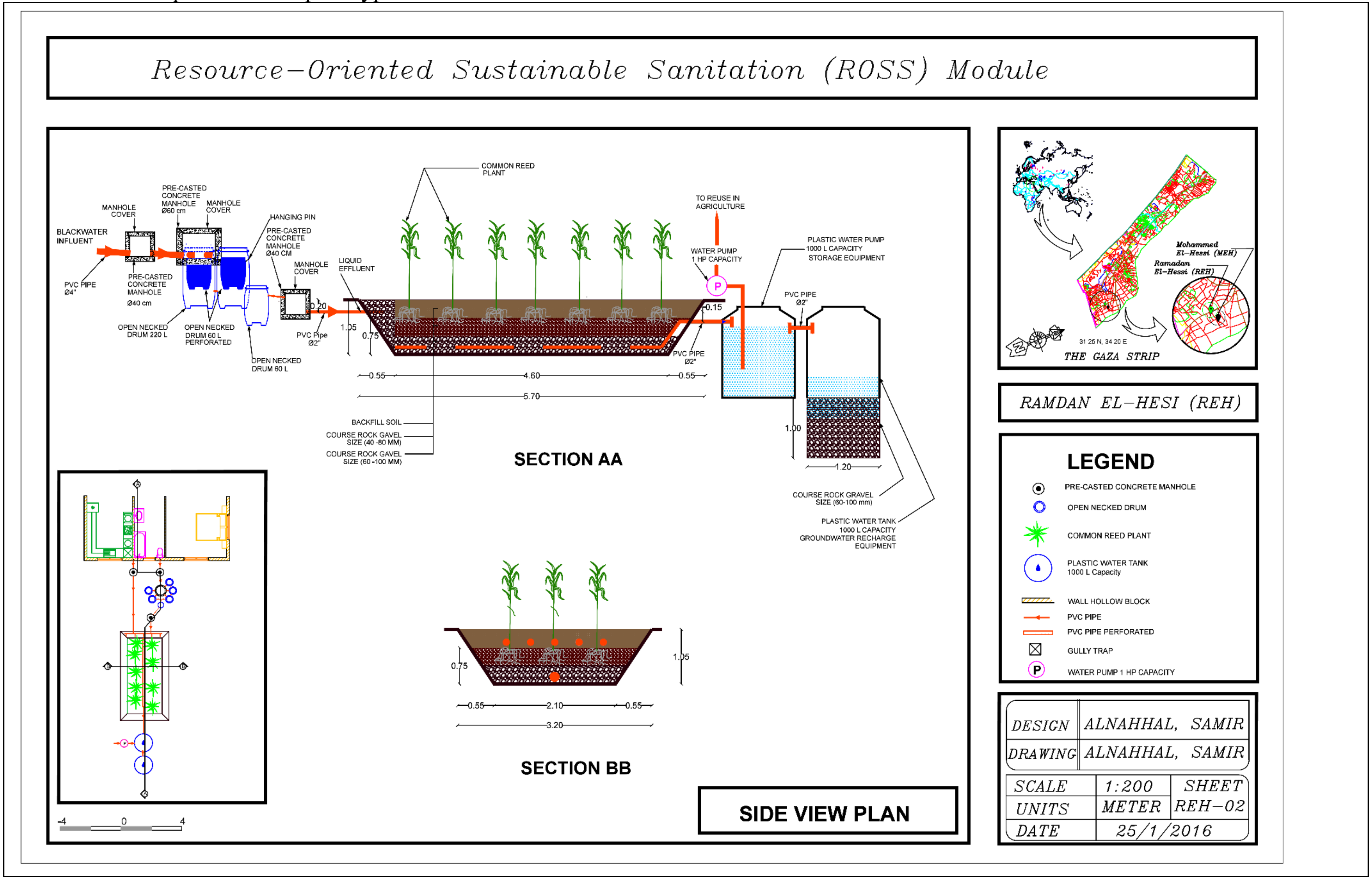
I.II. Side view plan for MEH prototype



I.III. Top view plan for REH prototype



I.IV. Side view plan for REH prototype



II. Palestinian standards and environmental limit values for reuse of treated wastewater in different applications

Quality Parameter (mg/l except otherwise indicated)	Fodder Irrigation		Gardens, Playgrounds, Recreational	Industrial Crops	Groundwater Recharge	Seawater Outfall	Landscapes	Trees	
	dry	wet						Citrus	Olive
BOD_5	60	45	40	60	40	60	60	60	45
COD	200	150	150	200	150	200	200	200	150
DO	> 0.5	>0.5	> 0.5	> 0.5	> 1.0	> 1.0	> 0.5	> 0.5	> 0.5
TDS	1500	1500	1200	1500	1500	-	1500	1500	1500
TSS	50	40	30	50	50	60	50	50	40
pH	6–9	6–9	6–9	6–9	6–9	6–9	6–9	6–9	6–9
Color (PCU)	Free	Free	Free	Free	Free of colored matter	Free of colored matter	Free	Free	Free
FOG	5	5	5	5	0	10	5	5	5
Phenol	0.002	0.002	0.002	0.002	0.002	1	0.002	0.002	0.002
MBAS	15	15	15	15	5	25	15	15	15
NO_3-N	50	50	50	50	15	25	50	50	50
NH_4-N	-	-	50	-	10	5	-	-	-
O.Kj-N	50	50	50	50	10	10	50	50	50
PO_4-P	30	30	30	30	15	5	30	30	30
Cl	500	500	350	500	600	-	500	500	400
SO_4	500	500	500	500	1000	1000	500	500	500
Na	200	200	200	200	230	-	200	200	200
Mg	60	60	60	60	150	-	60	60	60
Ca	400	400	400	400	400	-	400	400	400
SAR	9	9	10	9	9	-	9	9	9
Al	5	5	5	5	1	1	5	5	5

Quality Parameter (mg/l except otherwise indicated)	Fodder Irrigation		Gardens, Playgrounds, Recreational	Industrial Crops	Groundwater Recharge	Seawater Outfall	Landscapes	Trees	
	dry	wet						Citrus	Olive
Ar	0.1	0.1	0.1	0.1	0.05	0.05	0.01	0.01	0.01
Cu	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
F	1	1	1	1	1	1.5	1	1	1
Fe	5	5	5	5	2	2	5	5	5
Mn	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Ni	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Pb	1	1	0.1	1	0.1	0.1	1	1	1
Se	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Cd	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Zn	2	2	2	2	5.0	5.0	2.0	2.0	2.0
CN	0.05	0.05	0.05	0.05	0.1	0.1	0.05	0.05	0.05
Cr	0.1	0.1	0.1	0.1	0.05	0.5	0.1	0.1	0.1
Hg	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Co	0.05	0.05	0.05	0.05	0.05	0.05	1.0	1.0	0.05
B	0.7	0.7	0.7	0.7	1.0	1.0	0.7	0.7	0.7
FC (CFU/ 100 ml)	1000	1000	200	1000	1000	50000	1000	1000	1000
Pathogens	Free	Free	Free	Free	Free	Free	Free	Free	Free
Amoeba & Gardia (Cyst/L)	-	-	Free	-	Free	Free	-	-	-
Nematodes (Eggs/L)	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1

- Undefined

III. Field measurements and laboratory analysis of some indicative parameters in blackwater and greywater samples

III.I. First-round results

Sampling location	Temperature	Acidity /Basicity	Electrical conductivity	Chloride Cl	Nitrate NO_3 - NO_3	Ammonia NH_4-NH_4	Total Kjeldahl Nitrogen	Phosphorus PO4-P	Total solids TS	Total suspended solids	Total dissolved solids	Settleable solids	Total organic matter	Biological oxygen demand	Chemical oxygen demand	Faecal coliform
	°C	pH		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	ml/l	mg/l	mg/l	mg/l	CFU/100 ml
SP1	28.9	7.2	>2000	1390	0.3	110	245	23.6	4364	1756	1756	21.0	4299	1300	4830	$5.9*10^5$
SP2		7.0	1055	1220	-	35	20	4.9	2744	139	139	2.0	290	380	950	$5.5*10^3$
SP3	28.2	7.7	>2000	1370	0.7	190	209	14.0	3401	751	751	8.5	2236	720	1792	$7 *10^4$
SP4	26.2	7.4	>2000	1475	1.3	86	95	5.3	2811	131	131	<0.5	301	310	740	$4.2 *10^3$

III.II. Second-round results

Sampling location	Temperat ure	Acidity /Basicity	Electrical conductiv ity	Chloride Cl	Nitrate NO_3 - NO_3	Ammonia NH_4- NH_4	Total Kjeldahl Nitrogen	Phosphor us PO4-P	Total solids TS	Total suspended solids	Total dissolved solids	Settleable solids	Total organic matter	Biological oxygen demand	Chemical oxygen demand	Fecal coliform
	°C	pH	µS/cm	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	ml/l	mg/l	mg/l	mg/l	CFu /100 ml
SP1	22	7.8	795	1280	0.77	108	144	26	4037	1547	2590	20.2	4153	1250	4732	$6.8 *10^5$
SP2	20.3	7.5	1430	1104	-	31	50	5.1	2619	126	2493	1.7	270	357	910	$6.2*10^3$
SP3	20.5	7.8	1860	1380	0.9	127	143	17	3340	571	2769	9.1	2009	670	1660	$6.4*10^4$
SP4	19.4	7.5	1770	1300	1.9	80	92	6.7	2758	65	2693	<0.5	295	228	590	$2.98*10^3$

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