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Charcoal vertical gardens as treatment of drainwater for irrigation reuse

- a performance evaluation in Kibera slum, Nairobi

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Abstract

Lack of wastewater treatment and proper disposal is common in low-income urban areas. Wastewater is poured out on the streets or in drenches that mix with rainwater and other waste, eventually polluting downstream rivers, lakes and water sources. The pollution affects farmers that reuse the drain water as irrigation water, the people living in the urban area as well as settlements downstream of these areas. Large wastewater treatment systems are hard to implement in these areas due to lack of space and funding. Affordable small-scale water treatment solutions in these areas could benefit the health, food security and lower water-stress in the community.

This study assessed a charcoal filter in the form of a vertical garden as a small-scale irrigation water treatment system. The vertical garden was placed at the dried-up Nairobi dam in Kibera, the biggest slum in Nairobi, Kenya. The wetland that used to be the Nairobi dam is used by local farmers in Kibera to collect water and grow crops. However, the dam receives the majority of all the drain water that is discharged from Kibera. The drain water is a mix of greywater, rainwater, general waste, and excreta from public latrine pits and toilets. The water is then reused by the local farmers with no treatment, posing as a health risk for consumers and the farmers themselves. The study examined the microbiological and chemical quality of the drain water, the reduction of the filter, and the quality of the effluent water from the vertical garden.

Samples of drain water and effluent water were collected twice a week for five weeks, measuring the prevalence of Escherichia coli (E. coli), Coliforms, and Salmonella as well as the Total solids (TS), Volatile solids (VS), Fixed Solids (FS), Biochemical oxygen demand (BOD), pH, and Electrical conductivity (EC). Extra samples were collected during the last week and were brought back to the SLU lab in Sweden where Total nitrogen, Total Phosphorus, and Chemical oxygen demand was measured.

The results showed that the drain water used for irrigation was of a non-consistent quality during the sampling period. There was a strong correlation of increased runoff from Kibera due to heavy rains and presence of E. coli and coliforms. Salmonella presence was low or absent and not influenced by runoff. The results also showed a clear reduction of microbes from the filtration treatment in the garden. However, the filter was not able to reduce Salmonella. The BOD and TS were reduced in the vertical garden, but the effluent carried solids in form of charcoal residue from the filter. Nitrogen decreased in the vertical garden due to crop uptake while phosphorus was relatively unimpacted. The effluent water was of higher quality than the influent due to these reductions, but the filter was not able to reduce enough during heavy rainfall and runoff.

The study showed that the local charcoal was capable as a filter medium and that a vertical garden can be an easy and affordable water treatment solution.

Keywords: Drain water, wastewater, wastewater reuse, irrigation, vertical garden, charcoal, charcoal filter, Kibera, Nairobi

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Referat

Brist på reningsverk för avloppsvatten är vanligt i stadsmiljöer med låg inkomst. Avloppsvattnet hälls ofta ut på gatan eller i diken där det sedan blandas med regnvatten och annat avfall. Detta påverkar bönder som återanvänder det förorenade dräneringsvattnet som bevattningkälla och övriga lokalbor som lever nedströms utsläppspunkterna. Stora avloppsreningsverk är svåra att implementera i slumområden, både av brist på utrymme och på avsaknad finansiering. Implementering av billiga och småskaliga vattenreningssystem skulle kunna främja den allmänna folkhälsan och minska vattenstressen i samhället.

Denna studie analyserade ett kolfilter i form av en vertikal trädgård som ett småskaligt reningsverk för bevattningsvatten. Den vertikala trädgården placerades vid den uttorkade Nairobi dammen i Kibera, vilket är den största slummen i Nairobi och Kenya. Våtmarken som brukade vara dammen används av lokala bönder som odlingsmark och bevattningskälla. Våtmarken i sig tar emot majoriteten av dräneringsvattnet från Kibera. Dräneringsvattnet i sin tur är en mix av gråvatten, regnvatten, avfall och avföring från allmänna latriner och toaletter. Detta vatten återanvänds sedan som bevattningsvatten av de lokala bönderna utan reningsbehandling, vilket utgör en hälsorisk för både konsumenter av grödorna och för bönderna själva. Mätningar utfördes på både mikrobiologiska och kemiska parametrar för att uppskatta kvalitén på det nuvarande bevattningsvattnet, reduktion av dessa parametrar i filtret, samt kvalitén på det utgående vattnet från den vertikala trädgården.

Prover från dräneringsvattnet och det utgående vattnet togs två gånger i veckan där Escherichia coli (E. coli), koliforma bakterier, salmonella, torrsubstans (TS), glödförlust (VS), biokemisk syreförbrukning (BOD), elektrisk konduktivitet (EC) och pH mättes. Extra prover togs under den sista veckan av provtagningen som sedan transporterades tillbaka till SLU:s labb i Sverige där totalt kväve, total fosfor och kemisk syreförbrukning mättes. Resultaten visade att dräneringsvattnet som används för bevattning varierade i kvalité under provtagningsperioden. Det fanns ett tydligt samband mellan ökad avrinning från Kibera på grund av kraftig nederbörd och förekomsten av E. coli och koliforma bakterier. Resultaten visade också en tydlig reduktion av E. coli, koliforma bakterier, TS, BOD och COD till följd av filtreringen i den vertikala trädgården. Däremot var filtret inte kapabelt att reducera salmonella. Totala kvävet minskade i filtret medans den totala fosforn var lägre och relativt opåverkad av filtreringen. Det utgående vattnet från trädgården var av högre kvalité än dräneringsvattnet. Men under perioder med hög avrinning var mängden av E. coli och koliforma bakterier ut ur filtret ändå för hög för att låta vattnet återanvändas som bevattningsvatten.

Studien visade därmed att det loka kolet var väl fungerande som ett filtermedium och att vertikala trädgårdar kan vara billiga och lättbyggda lösningar för vattenrening.

Nyckelord: Dräneringsvatten, avloppsvatten, återanvändning av avloppsvatten, bevattning, vertikal trädgård, kol, kolfilter, Kibera, Nairobi.

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Preface

This master thesis is the accumulated result of a minor field study (MFS) conducted in Nairobi, Kenya. The project was sponsored by the Swedish International Development Agency (SIDA) and has been assisted by the University of Nairobi, Department of Public Health Pharmacology & Toxicology, throughout the process. The students responsible for this report are scholars of environmental and water engineering, with a special interest in small scale water treatment solutions. This report will engage the theme of small-scale water treatment by evaluating the performance of a charcoal filter, functioning as a vertical garden.

Luis Fernando Mercado-Perez, PhD student at the Department of Energy and Technology, Swedish University of Agricultural sciences, was the supervisor. Dr. Sahar S. Dalahmeh, researcher at the Department of Energy and Technology, Swedish University of Agricultural sciences, was the subject reviewer. Dr. Nduhiu Gitahi, Principal Technologist at the Department of Public Health Pharmacology & Toxicology, University of Nairobi, was the supervisor in Nairobi.

We want to specially thank everyone at the Department of Public Health Pharmacology & Toxicology at the University of Nairobi for their hospitality, professionalism, and for all the help we received during our long hours in the lab. Thank you for going out of your way to make sure we felt welcome and thank you for making Nairobi our home away from home. We also want to thank Patrick Ule Mmoja, our assistant in Kibera, for his hospitality and expertise. Thank you for managing and watering the vertical garden and for guiding us in Kibera.

Special thanks to Dr. Nduhiu Gitahi who was a key person in the making of this thesis. The work would have been a lot harder without your expertise and all the help you gave us. We truly appreciate that you took your time to make sure we had everything we needed, and for personally committing to our project. You provided knowledge, information, and solutions when we needed them. Thank you for all the support we received, we truly enjoyed working with you.

Many thanks to Sahar Dalahmeh for all the help we received both in Sweden and in Nairobi via email. We really appreciate all your help in providing lab equipment, instructions, experience, and for all the questions you have taken your time to answer during the study. We also want to give you a special thanks for sparking our interest in small scale water treatment solutions many years ago, without you we would not be conducting this thesis today.

We also want to show our appreciation to Luis Fernando Perez-Mercado who has taken his time helping us in the lab, answering many questions on email and Skype. Luis has provided us with a lot of knowledge, experience and support throughout the study.

Lastly, we would like to thank our families and friends for their support during this study.

All of this study has been a joint feature by both authors with equal workload and responsibilities. The thesis has been written together with shared responsibilities of all sections. However, certain sections have been under the main responsibilities of a specific author. A few examples of Gabriella Rullander's main responsibility sections are: Sections 1.1, 2.3, 3.1, and 5.6.1. A few examples of Niclas Grünewald's main responsibility sections are: Sections 1.6, 2.4.1, 3.3, and 5.6.6.

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Populärvetenskaplig sammanfattning

Att Rena Vatten och få Betalt i Mat: Det Bästa med en Vertikal Kolträdgård

Att ha vatten av hög kvalitet lätt tillgängligt betraktas som en mänsklig rättighet, eftersom det både påverkar en människas livslängd och livskvalité. Rätten till säker vattenförbrukning och hantering kan anses självklar i vissa länder, allra helst i Sverige. Men sanningen är att mer än en tredjedel av världens befolkning saknar rättighet till rent vatten. Dessutom kan dålig hantering av avfall, i kombination med en bristande vattenhantering generera sjukdomsspridning och få förödande konsekvenser för människors hälsa. Mer än 160 000 barn under 5 år dör varje år tillföljd av bristande vattenhantering (WHO, 2018).

Figure 1: Vertical charcoal garden after 4 weeks in the field. Authors picture

Sannolikheten att bli nekad sina mänskliga rättigheter, eller påverkas av vattenburna sjukdomar ökar för den som lever i ett slumområde. Detta eftersom slumområden ofta saknar ordentlig infrastruktur, avlopps- och dricksvatten hantering och präglas dessutom av tätbefolkade områden. Kibera är Kenyas mest tätbefolkade slum, här vattnar invånarna sina odlingar med vatten från en närliggande damm. Vattenkvaliteten i dammen är förorenat, speciellt vid mycket nederbörd då mängden dräneringsvatten från avrinningsområdet ökar. Dräneringsvattnet har bland annat passerat genom överfyllda latriner på sin väg ned ifrån de centrala delarna av slummen. Vattned som ansamlas i Kibera dammen är därför oftast inte av tillräckligt god kvalite för att användas som bevattningsvatten.

Hur designades trädgården och varför?

Detta projekt har utformats med ett långsiktigt mål att förbättra de mänskliga rättigheterna för de som bor i Kibera, genom att fokusera på att hitta ett enkelt, billigt och platsbesparande sätt att rena invånarnas bevattningsvatten. En annan sak som är viktig vid design av reningstekniker är att lösningen är anpassad efter målområde och grupp. I detta fall innebar det att designa ett filter med material som var billiga och enkla att få tag på. Dessutom skulle tekniken vara enkel för lokalinvånare att konstruera och det skulle finnas något som lockar till egen användning och investering.Som svar på detta designades och konstruerades en vertikal kolträdgård som implementerades vid Kibera dammen, se Figur 1.

Den största utgiften i detta projekt var inköp av kol. Övrigt material som filtret byggdes av (säckväv, plastflaskor, plasthink och spenatsticklingar) var lätta att komma över i Kibera och oftast gratis. Teknikmässigt så var filtret enkelt att konstruera, men ett tidskrävande och tungt jobb. Speciellt med avseende på att krossa och sila kolbitar till rätt storlek.

Kolträdgårdens design och konstruktion kan ses i Foto 1. Fotot visar en säckväv fylld med krossat kol (mestadels partiklar av storlek 1,4 till 1,7 mm). Plastflaskor har delats i tu och packats med jord. Sedan har kolet i säcken varvats med flaskorna som placerades med jordytan mot säckväven (som en cirkel) och mitten på flaskhålet markerades därefter utanpå säcken med en markeringspenna. När filtret hade fyllts med kol och flaskor så skars det små hål vid markeringarna med skalpell och spenat sticklingar trycktes försiktigt genom säckväven och in i plastflaskan.

Vilka resultat gav användandet av trädgården?

Filtret vattnades tre gånger per dag med vatten från dammen och reningseffekt analyserades sedan under fem veckor med hjälp av mikrobiella och kemiska vattenanalyser utförda på in och utgående vattenprover genererade av trädgården. Trädgården planterades med spenat sticklingar, en lokal favoritgröda, och dess utveckling noterades under veckorna som gick. Resultaten tyder på att trädgården har en hög (över 60%) retningseffekt med avseende på vissa mikroorganismer (E. coli och Coliforma bakterier), vilket är positivt då det är dessa som ofta leder till kolerautbrott! Samtidigt överraskade provresultat för Salmonella virus, som istället såg ut att kunna tillväxa i filtret. Att salmonella inte renades är intressant och bör undersökas vidare, då detta kan bero på filtrets unga ålder och att det finns möjlighet för en ökad reningseffekt över tid. I övrigt gav de andra kemiska laborationer indikationer att kolträdgården är bra på att filtrera och adsorbera organiskt material och näringsämnen. Dessutom blev spenaten i trädgården 50% större under fältperioden och analyser visar att de flesta bladen är säkra att äta!

Designen var sammanfattningsvis billig, enkel att bygga, platsbesparande och genererade föda, som spenat, till den som använde sig av den. Samtidigt hade den en renande effekt på Kiberas bevattningsvatten från Nairobi damm, med avseende på flera aspekter.

List of Abbreviations and Definitions

BOD	Biochemical oxygen demand
BOD_5	BOD measurement with 5 days incubation
CFU	Colony forming units
COD	Chemical oxygen demand
FAO	Food and Agriculture Organization
FC	Fecal coliforms
FS	Fixed solids
KES	Kenyan Shilling
IQR	Inter Quartile Range
SD	Standard Deviation
TC	Total coliforms
Tot-N	Total Nitrogen
Tot-P	Total Phosphorus
TS	Total solids
VS	Volatile solids
WHO	World Health Organization

Box plots show how a set of data is distributed and contains the median value (red line), the lower and upper quartile (Q1 & Q3) showed by the box's upper and lower boundaries (blue lines). 50% of the data are within the box range. The boxplot also contain so-called "whiskers" representing the "Maximum" and "Minimum" of the distribution. If whiskers are present, they are shown as solid lines emerging out of the box on either the upper or lower side. There are also so-called outliers that are "extreme-values" that do not fit the normal distribution of the data. The outliers are either $1,5 \cdot$IQR (interquartile range) above or below the upper or the lower quartile and are marked with a red +.

Drain water is a mixture of rain water and domestic wastewater.

Effluent water refers to water coming out of the tap of the bottom of the garden.

Influent water refers to water that is collected from the sample collection point and put in to the vertical garden.

P-value is obtained from the Wilcoxon ranksum test that compares medians of independent samples to produce the P-value. If the P-value is below 5% it rejects the null hypothesis. The null hypothesis in the wilcoxon ranksum test is based on the two sets of data having equal medians. The test assumes that the samples are independent which is not the actual case for most of our samples and should therefore be considered when observing the P-values.

Stable weather conditions are referred to during the report and signifies none to light rainfalls. This type of weather was present during the majority of the sampling period. This weather condition does not include heavy rainfalls and floods.

Spinach is referred to in this thesis but does not accurately represent the English definition of spinach. The spinach referred to is per definition Swiss Chard, which is derived from spinach and beetroot. Swiss chard is commonly used in many Kenyan dishes, where it is called Mboga. Mboga was translated to spinach and is known as spinach in the common tongue, hence it will be referred to as spinach during the remainder of this thesis.

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1 Introduction

Everyone deserves access to high quality water and a life unaffected by waterborne disease, regardless of who you are or where you live. However, the reality is that many people still live without proper wastewater systems and that humans keep dying due to waterborne diseases (WHO, 2018). The western idea of a standard wastewater treatment system such as sewage pipelines and wastewater services, big enough to facilitate cities, is not always an appropriate solution. Instead, a suitable wastewater treatment differs depending on the location and the targeted area's wastewater quality. Wastewater treatment systems need to be custom-made for a specific situation, in order to generate the highest water quality result possible.

People living in poor, high-density populated areas in developing-world-slums are exposed to a low functioning, non-circular ecosystem without proper wastewater treatment. As a result, they become vulnerable to diseases such as cholera and typhoid outbreaks. There is a need for innovative solutions that are custom-made for the social and environmental structures associated with low-rise settlements. The future of wastewater solutions for slums need to consider the economic challenges combined with the often-illegal status (non-governed) aspects of settlements. The solutions should also suit the limitations associated with high density populated areas, such as the amount of human waste generated and the limited access to space for treatment implementation. The purpose of this field study was to design and evaluate a suitable treatment solution focused on treating polluted drain-water in Kibera, the largest slum in Kenya. The drain-water gathered towards the Nairobi dam and was at the time utilized as a source of irrigation water by local farmers.

Biochar and active carbon have been commonly used as filter medium to treat different types of wastewater, due to their great adsorption characteristics. Another technique that has been implemented and analysed as a treatment solution in slum areas are soil packed sack gardens, also called vertical gardens. The vertical garden has been measured for its effectiveness in treating grey-water and deemed ineffective for its treatment aspects as a sand filter. However, the vertical garden has been considered successful in other terms, especially for its easy design and associated crop yield.

In Kibera, vertical gardens are an already established urban gardening technique adopted by some locals due to its space saving qualities. Furthermore, the most common used energy source for cooking in Kibera is charcoal. Charcoal can be found throughout the slum and could be described as a local version of biochar but with a less controlled origin and differing pyrolysis technique compared to industrial-bought biochar. For a visual representation of a vertical sack garden and available charcoal offered by vendors in Kibera, see Figure 2.

The designed treatment solution in this thesis combines the filtering possibilities of local charcoal from Kibera with the positive aspects associated with a vertical garden. The upgraded designed version will be known through out the thesis as a: charcoal vertical garden, see Figure 1. The filter was given a design that would be as simple and inexpensive to build as possible, while keeping the positive space-saving aspects of a vertical garden. Given the fact that vertical gardens have already been established in the area and that the filter can increase the users sense of food-security, there is a further incentive for locals to want to invest in this prototype in the future.

The goal was for farmers to be able to grow crops whilst simultaneously sanitising the drain-water which is re-used as irrigation water. The main choice to conduct this research and to build, implement and evaluate a charcoal vertical garden was based on the believed potential of the designed prototype in question. That is, that the filter could have a positive effect on the quality of water irrigation and food security among its users. Striving towards the final goal of providing a higher living standard for the locals in Kibera.

Figure 2: Local charcoal sold by local vendors (left) and a vertical sack garden farming Kale, owned by locals (right). Photos taken by authors.

1.1 Problem Statement

Emerging-world slums are usually self-built areas, not organized by formal society, and governed bottom-up. The areas are often made up of low-rise buildings, constructed from local building materials and inhabits many people within one area. Issues that characterize slums with high population densities is the lack of availability of services like water, sanitation and waste management as well as a underdeveloped infrastructure (Robertson and Dagdeviren, 2009).

Inhabitants of Kibera are familiar with these issues. Kibera is believed to be the second highest density slum in Africa. Here, the average person is given approximately 10 m^2 of living space (Schouten and Mathenge, 2010). The informal settlement is expanding, due to both natural population growth and to urbanisation. Urban living offers many benefits to locals, such as a wider job opportunity in Nairobi. However, the congested living arrangements can lead other issues, one of which is a higher density of human waste. Since the area lacks proper waste disposal most waste gathers in Kibera's drainage systems and is spread downstream, creating a small river when mixed with rainfall. The run-off moves towards the Nairobi dam, where it is later collected and re-used as irrigation water by local farmers. The re-used water is microbial polluted with pathogens and using it as irrigation water on crops further contributes to health issues in Kibera. The crops grown in the area are therefore carriers of waterborne diseases, like cholera (UN, 2003).

Implementing conventional sanitation systems to improve the run-off/irrigation water quality, such as sewage networks or larger treatment systems, in slum-areas can be challenging. The high cost and space required for implementation and the usually larger amount of water needed to operate conventional systems make them unsuited for slums like Kibera. With one study showing that 32 % of the children living in Kibera are suffering from diarrhea, caused by unsanitary water and environment, there is a need for space-saving, simple and affordable water treatment technologies (Kimani-Murage and Ngindu, 2007).

1.2 Report starting point

Using organic material from forestry or agriculture to produce biochar or active carbon through the pyrolysis process is a well-known procedure. Both biochar and active carbon have been studied for their ability to treat wastewater. There is also research on the effect that different grain-size of biochar filter can have on the water treatment efficiency.

Vertical gardens have also been a subject of studies in the past. Some studies have focused on the positive effect vertical gardens can have on communities due to its high yield and space-saving qualities, especially in dense urban areas. Research has also shown the willingness of local adaption to the vertical farming tool and has given an understanding of what type of crop is best suited for the technology. In other studies, the focus has been on vertical sand gardens, and the positive and negative effect of using sand particles and crops as a filter for water treatment.

However, there is a knowledge gap to be filled regarding biochar vertical gardens, and evaluations of filters created from local charcoal. The project has a unique starting point, with much previous research to be found on biochar and vertical gardens alone and gives an opportunity to combine and evaluate the two together. Also, since the effect biochar can have on purifying water depends on its origin and how it has undergone pyrolysis there is a great interest in testing the local charcoal from Kibera, as it is yet to be studied for its treatment properties.

The polluted drain-water source, designated for treatment during this project, was collected from the Nairobi Dam. Here, it was utilized as irrigation water posing as a direct health risk for the local farmers and a secondary risk for crop consumers in Kibera. Conducting this project today becomes important for those at risk as the study provides information of the drain-water quality and evaluates a method of treatment. Especially, if the result of the thesis is satisfactory, the small-scale solution was designed to promote possible re-production of the prototype by locals.

1.3 Goal and Objectives

The long term goal is that the thesis will contribute to advancements in developing wastewater treatments suited for people living in areas where finances, space and knowledge of simple wastewater treatments have been restrictive factors in developing possible sanitation technology.

The goal will be pursued by focusing on objectives carried out during a two month field study in Kibera, Nairobi. The objective was to build, implement and evaluate how efficient a filter made of local charcoal could function as a small scale treatment for drain-water re-used as irrigation water.

1.4 Research questions

This report is focused on answering the five questions stated below.

1. How efficient is the charcoal vertical garden in reducing E. coli, coliforms, Salmonella spp., TS, VS, FS, BOD_5, and COD from the water gathered at the Nairobi Dam?
2. How are the levels of the plant nutrients Tot-N and Tot-P in the water affected when passing through the vertical garden?
3. How capable is the vertical garden in cultivating spinach and what levels of possible contamination are the plants exposed to in terms of E.coli, Salmonella spp. and Coliforms?
4. How well does the local charcoal function as a filter medium in terms of its retention time and non-clogging functionality?
5. Is the quality of effluent water, appropriate to be re-used as irrigation water?

1.5 Assumptions

Throughout the thesis the assumptions listed below have been made. Some of which have influenced the outcome of the study:

1. The influent water source was assumed to be non-toxic, in terms of heavy metal exposure.
2. The water quality of the influent water was assumed more polluted than greywater but less than pure waste water, in terms of microbes and amount of solids in the water.
3. The hydraulic water loading rate (HLR) was constant throughout the sampling period.

Due to the time limits of the field work, the vertical garden was built before testing the water run-off quality in the Nairobi Dam. The design of the garden was based on assumption 1 and 2 listed above. For example, the assumed water quality influenced the chosen charcoal grain size. The grain sizes were chosen to minimise clogging while maximising removal efficiency of contamination, according to literature and assumed water quality. The water quality assumptions 1 and 2 were based on visual information gathered when scouting for an appropriate field-site and from advise given to us by the University of Nairobi.

The chosen HLR was assumed to be constant throughout the sampling period. This includes assuming that the watering regime in Kibera was followed through out the 5 weeks and that top-part of the vertical garden was placed correctly on top of the sack after each water load. The top part of the garden was also assumed to be working and indeed protecting the charcoal from receiving heavy precipitation (which otherwise would alter the HLR).

1.6 Limitations and restrictions

The study was also influenced by a number of different limitations. The limitations included:

1. Space-requirements and regulations for bringing equipment and chemicals on flight from Sweden to Kenya
2. Project budget
3. The choice of implementation location for the vertical garden and the selected sample collection point.
4. Safe working hours in Kibera.
5. Two months total time to conduct field work.

Even though Nairobi University was generous enough to assist with much laboratory equipment and personal assistants, conducting certain experiments is a cost. To minimise expenses and strain on the hosting university much of the lab equipment used in the thesis had to be brought from SLU. The planned research and laboratory work could therefore only be decided according to the amount of equipment and analysing tools that could be brought on the flight from Sweden to Kenya.

The location of the vertical garden and choice of sample collection point was also a limited. This due to safety issues regarding an election being held in the Kibera area and the issues regarding the density of Kibera housing and popultaion.

The watering times of the garden was also limited. The garden had to be irrigated with water during daylight, to ensure safe passage to and from the field site for Patrick Ule Mmoja, a Kibera resident who was hired to water and maintain the vertical garden.

There was also a limitation of time from arrival to departure (two months in total) in which both the construction of the garden, sample collection, and lab work was to be achieved. Due to the time limitation, a few restrictions of the thesis had to be made:

1. Analysing only one prototype.
2. Analyse water collected from only one point in the Nairobi dam.

This thesis focuses on the source of contamination found in one point of the Nairobi Dam and does not elaborate on calculations regarding the amount of Kibera run-off or the size of the run-off area itself.

The results generated by testing the in and effluent water represents data for 5 weeks, from one vertical garden and with water collected from one and the same sample point.

1.7 Challenges during study

There were a number of challenges during the study, some expected and some unexpected. The first challenge was to crush the amount of charcoal needed to build the vertical garden. The crushing of the charcoal had to be made by hand since the vertical garden is aimed to be an affordable solution that does not require any heavy machinery. The crushing and filtering of the charcoal proved to be as much of a physical effort as expected and required almost one week of inventive ways to crush charcoal.

Several of the experiments conducted during the sampling period were dependent on the water quality. For example, the volume used when analysing TS and VS varied depending on the number of particles in the sample and the dilution factors suited for microbiology analyses differ depending on amount of organisms found in the sample. BOD measurements require results within specific ranges, that too depends on the water quality. Therefore, the first week of testing was focused on getting an understanding of the water qualities, so that it might benefit choices of volumes, dilutions and ranges for the rest of the sample period.

There was also a challenge concerning the available distilled water used analyses during the sampling period. The distilled water varied in quality from time to time. This was most palpable during BOD measurements, as they were dependent on the DO levels of the distilled water.

2 Literature Review

2.1 Irrigation water treatment systems

Clean irrigation water of high quality is one of the four major factors for crop health management (Cook, 2000). The two considerable disincentives for irrigation water are pathogens and salinity. Pathogens can be present in irrigation water and cause diseases for both plants and consumers (Stewart-Wade, 2011). Loss of yield or poor crop health management can impact both economically and/or health wise, and in some cases be negative for food security in a specific area (Hong and Moorman, 2005). There is a number of different technologies used to treat irrigation water to minimize this risk. Treatment technologies can be chemical, physical or ecological solutions depending on the target pathogen. Different chemicals can be used to improve irrigation water quality such as chlorine or ozone. Physical treatment, and other treatment systems not using chemicals, can be found in the form of filters, heating systems, or the use of radiation treatment such as UV. Ecological treatment systems can be in the form of slow filtration with natural sand filters, wetlands, or natural ponds (Raudales, 2014).

2.2 Vertical gardens

Vertical gardens are usually cylindrically shaped with the plants stacked vertically on the sides and sometimes a few plants on the top of the cylinder. The sides of the garden can be made out of different materials such as bricks stacked in a cylindrical tower shape or in the form of a large weave bag (Morel and Diener, 2006). The center of the vertical garden is usually filled with soil. Sometimes, a pipe containing rocks is put in vertically in the center of the garden to promote drainage. Vertical gardens are usually used in rural areas with dense populations where space available for gardening is limited. Water scarcity has also been a factor in many of these areas which has led to other sources of water being used as irrigation water for the vertical gardens. Greywater is one of the sources that has commonly been used as irrigation water for vertical gardens. Some studies have been made on the filtering impacts the vertical gardens have on the greywater. Greywater is commonly defined as household wastewater from showers, bath, laundry, kitchen, sinks and household machines. In other words, it's all the household wastewater excluding the toilet, bidets or other heavily polluted waste sources (Li et al., 2009).

There is little research on vertical gardens in general with the few studies existing focusing mainly on greywater treatment using vertical gardens. The benefits of vertical gardens have been pointed out to be that they are cheap and easy to construct, easy to use, and requires little to no monitoring when in place (Morel and Diener, 2006). Generated crops from the garden can also have a positive impact on food security for the owner. However, the studies have also shown that the vertical gardens sometimes tend to clog depending on the soil and drainage design of the vertical garden (Eklund and Tegelberg, 2010). There are few to none results available to showcase the treatment efficiency of vertical gardens at this point.

2.3 Charcoal in water treatment systems

Low-cost solutions for water treatment in developing countries is an all more trending field of science. Low-cost solutions often focus on point-of-use treatments using affordable and accessible materials. One of the more trending materials for drinking- and wastewater treatments is charcoal and charcoal ashes, which is usually both affordable and accessible in rural developing areas (Gupta and Chaudhuri, 1994) (Kanaujia et al., 2014) (Gupta et al., 2009). Charcoal has shown to be able to reduce toxic organic compounds, taste, odour, chemical oxygen demand and heavy metals (Katal et al., 2012) (Agrawal and Bhalwar, 2009). Tests has also shown that wooden charcoal can have a substantial impact in small scale water treatment filters. The tests showed a large increase in removal of fluoride, arsenic and coliforms when wooden charcoal was added to the filters (Kanaujia et al., 2014).

2.3.1 Terminology

Biochar, charcoal and activated carbon are all products produced from organic material. All three sources originate from biomass, however, charcoal is typically associated with wood and utilized as a fuel for cooking whereas the term biochar was commonly associated with soil conditioning and water remediation whereas active carbon almost always is associated with filter treatment (Berger, 2012).Active carbon is also made from biomass via pyrolysis, but has undergone activation, for example by using additions of chemicals to enhance the carbons efficiency in filter treatment (Lehmann and Stephen, 2015).

2.3.2 Biochar in practice

According to Lehmann and Stephen (2015), re-introducing biomass into soil is an environmental positive approach to capture and storage carbon dioxide as it can endure for thousands of years. Lately there has been an interest in expanding the usage of biochar and utilizing it as a filter medium. Biochar is also a low-cost investment in comparison to other adsorption materials which makes it an appropriate option for low-cost projects (Berger, 2012). Properties associated with biochar efficiency as a sorpent is its specific surface area, pore size distribution, ion-exchange capacity and hydrophobicity qualities. These properties can vary greatly depending on the biochar source and pyrolysis technique. That is, the biomass source, the residence time and the temperature during pyrolysis affect the biochars properties as a contamination sorpent (Ahmad et al., 2014). For example, pyrolysis temperatures lower than 400 Celsius can generate a specific surface area lower than 10 m^2g^{-1}, whereas a pyrolysis temperature above 550 degrees can result in a specific surface area greater than 400 m^2g^{-1} (Lehmann and Stephen, 2015).

Biochar is composed of a magnitude of micro, meso and macropores. They make up most of the biochar surface area and as a result much of the sorption of organic materials is obtained by the pore filling qualities of biochar. Newly made biochar also has a greater hydrophobic surface area than older biochar as its surface is less oxidated. Such hydrophobic surfaces acts as a sorpent for other hydrophobic organic compounds (Gwenzi et al., 2017).

Studies have shown the efficiency of biochar removing inorganics and heavy metal pollutions such as phosphate, zinc and iron due to its cat ion exchange capacity, pore geometry and porosity (Uchimiya et al., 2010)(Cao et al., 2009)(Chen et al., 2011). However there is not as much research conducted on biochar and its removal efficiency regarding microbes. But from what has been studied, it becomes clear that biochar can act as a physical filter on microbes such as E. Coli or Protozoa, as the they can be large enough to be caught on the biochar surfaces during the filtration process. Also, for bacterial and viral cells of negative charge, there is chance of surface adsorption with possible generated die-off (Gwenzi et al., 2017). However, this might not be true for bacteria bigger than the biochar pore or for large biochar pores in presence of volatile matter, as the volatile matter might block the pores, resulting in a decrease of attachment area (Mohanty et al., 2014). Mohanty et al., (2014) also found that biochar with either the lowest polar surfaces or the greatest hydrophobic surfaces combined with the lowest volatile matter generated the highest removal of E. coli. Organic contaminants on the other hand, are mostly sorped by mechanisms such as pore filling and electro- and hydrophobic interactions.

If there is interest in treating a specific pollutant it is recommended that the biochar's surface charge, pH and surface area is examined beforehand, as this will determine the filters appropriateness as a sorpent. Additionally, it becomes important to have information of the biochar origin and pyrolysis technique. For example, high temperatures during pyrolysis often produce biochar of larger pore sizes and higher surface area whereas a lower pyrolysis temperature generate a higher amount of polar functional groups (Gwenzi et al., 2017). Further investigating properties such as the pH of a polluted aquatic source designated for treatment is also of importance as this can change the biochar properties. For example, a biochar surface is mostly negatively charged and due to electrostatic interactions, organic compounds can bind to the biochar surface. However, the surface charge is dependent on the pH and if the total generated pH becomes below that of the absorbents pH at zero charge, pH_{pzc}, the total net surface charge of the biochar would change from its natural stage (Inyang and Dickenson, 2015).

2.3.3 Biofilm

Filters that are exposed to stormwater has shown tendencies for biofilm development on grains and in pores. The wastewater quality is of extra interest, as it is the wastewater composition of microbial community which composes the base of all biofilm created in the filter (Kumar et al., 2017). Biofilm development is also affected by the filter porosity, electrical conductivity and organic loading rate (OLR) of the irrigated water supply. Irrigation water which contains a high concentration of salt and a low OLR have shown results of limited biofilm development (Perez-Mercado et al., 2019). The biofilm colonies can also be sensitive to changes in pH and temperature, where the optimum growths for bacteria found in aquatic solutions commonly is at a neutral pH and around a temperature of 40 degrees Celsius (Ells and Truelstrup Hansen, 2006). However, the risk of biofilm developing in a filter media is its potential to promote secondary growth of pathogenic bacteria (Shama Sehar, 2016).

Using biofilm as a removal technique through mechanisms such as biodegradation, biosorption and bio mineralization is a well-established procedure. The benefits of biofilm degradation are especially well-established for sand filters. During sand filter operations, raw water passes through the filter particles, feeding the biofilm colonies with organic matter and nutrients, which is a condition for biofilm development. As a result, water passing through filters with attached biofilm can have a sanitary effect on the effluent water, not only due to the biofilm breaking down nutrients such as nitrogen and phosphor but also by removing trapped pathogens and organic matter (Lazarova and Manem, 1995). The biofilm removal effect also depends on the thickness of the biofilm created, which is directly linked to the filter environment and the biofilms possibility to age. However, biofilm can influence the interaction between the surface of the filter media and the particles suspended in the incoming wastewater. Depending on the biofilms effect on filter hydrophobicity, hydrodynamic flow and roughness contributed by the media surface areas, removal efficiency might increase or decrease in the filter system (Afrooz and Boehm, 2016).

A biofilm developed on a filter can reduce the media's pore size and become an additional sorpent for microbe removal. Afrooz and Bohem 2006 compared the removal efficiency of bacteria in a combined filter made of sand and biochar with and without a developed biofilm. The results showed that the filter combination with developed biofilm was less efficient in removing pathogens than the one without biofilm. The study proves that biofilm can have an inhibited effect on a medias surface area. One reason for this that was discussed was the bacteria tendencies to attach to rough surfaces. This tendency could negatively affect filters hydrophobic interactions with the contaminations. However, the removal efficiency for a combined filter, regardless of biofilm development, was still greater than that of a single sand filter. This indicated that a pathogen attachment can increase in filters where the water-holding capacity is raised (Gwenzi et al., 2017).

Biochar compared to sand filters has been proven to retain greater amounts of nutrients, which further promotes biofilm development (Shama Sehar, 2016). Frankel et al., 2016 shows that biochar attached with biofilm has had a greater metal sorption than biochar without a present biofilm. In fact, results indicate a four times higher removal rate for iron and aluminum on biotic biochar. The study also showed that biochar with a developing biofilm was more effective at removing organic contaminants, in this case, naphthenic acids, than sterile biochar.

2.4 Wastewater reuse for irrigation

Wastewater has a history of being used in irrigation because of its nutrients and fertilization abilities. Wastewater includes domestic sewage containing human excreta as well as municipal wastewater. The reuse of wastewater in irrigation carries with it two separate recipients: the crops and the humans who will consume the final product. Wastewater might carry pathogens and therefore pose as a health risk to consumers. Wastewater might also carry chemical, organic and inorganic compounds that can affect crop yield as well as the environment. The wastewater can have a positive affect if it carries nutrients for crops but have a negative affect if toxic chemicals are present. The World Health Organization (WHO) has a major interest in wastewater reuse and how to minimize human health risks both for consumers and workers in the fields. The Food and Agriculture Organization (FAO) also has a major interest in wastewater reuse but focus on the agriculture, irrigation and environmental risks and benefits of wastewater reuse (FAO, 2003) (Mara and Cairncross, 1989).

The agricultural benefits from wastewater reuse are usually most prominent in developing urban areas with water scarcity and where municipal wastewater treatment plants are few or non-existent. The excreta and organic compounds in wastewater carry macronutrients such as nitrogen and phosphorus that are a valuable natural fertilizer and have a beneficial impact on crop yield. However, it is hard to predict the composition of wastewater and its chemical, biological or physical properties might have a negative impact on both agriculture and human health. Therefore, it is recommended that wastewater reuse is carried out with proper planning, management and monitorization (FAO, 2003) (Mara and Cairncross, 1989).

This section takes a closer look at specific parameters of interest, divided into microbiological parameters and indicators for assessing human health risks and chemical parameters for irrigation reuse.

2.4.1 Microbiological indicators and pathogens

2.4.2 Escherichia coli

Escherichia coli also called E. coli is a gram-negative bacterium that can be found in humans and animals' lower intestines. E. coli is generally anaerobic and is able to ferment sugar by producing organic acid and gas, called "mixed acid fermentation". E. coli is also able to ferment lactose which is one of its key characteristics used when isolating and counting the presence of E. coli (National Research Council (U.S.) et al., 1977). The majority of E. coli strains are harmless to humans, but some can cause severe food poisoning and diarrhea. Humans are usually transmitted from consuming raw meat, contaminated vegetables, raw milk or from contaminated drinking water (WHO, 2019) (WHO, 2018a). Some strains of E. coli have the ability to survive in the ground sediments and eventually contaminating the groundwater, causing drinking water pollution. E. coli is sensitive to sunlight, increased pH, salinity, increased temperature and high levels of dissolved oxygen (Curtis et al., 1992).

E. coli is one of the most commonly measured indicators of fecal contamination in water (UNICEF, 2019) (Ashbolt et al., 2001). An indicator is measured to indicate the presence of other parameters of interest. E. coli is a good fecal contamination indicator since it is universally abundant in human and warm-blooded animal excreta. E. coli also stays present in contaminated water sources but does not occur naturally without the presence of feces. The presence and quantity of E. coli can be measured using generally simple methods and the removal of E. coli in water treatment systems is comparable to other waterborne pathogens. These qualities fulfill the criterium of an ideal indicator for waterborne pathogens (Havelaar et al., 2001). For litterature concerning the measurement procedure of E. coli, see Appendix A.

2.4.3 Health risks

E. coli may not always be a health risk itself, but the presence of E. coli clearly indicates fecal contamination which is linked to a great number of pathogens. It is hard to estimate the health risk associated with a certain level of fecal contamination since the risk depends on the specific pathogens present combined with the hosts ability to withstand the infective pathogens. Therefore, one can only assume that no water containing any level of fecal contamination can be regarded as safe (ibid.).

2.4.4 Coliform bacteria

Coliforms is a large group of different bacteria that can be found naturally in the environment as well as human and warm-blooded animal feces. The definition of coliforms has varied and been updated a lot throughout history, but the coliform definition has had a great impact on sanitary research of water. Coliforms are used as an indicator of both fecal and environmental pathogens. The coliform group is large and is usually divided into sub-groups. The usual sub-groups are Total Coliforms (TC) and Fecal Coliforms (FC). E. coli is a sub-group to FC. These sub-groups are used to separate coliforms that occur in the environment ant those that comes from fecal contamination. Since fecal contamination is more probable to pose as a health risk it is important to separate them from other coliforms. If a water sample contains any TC it is usually sent for further testing to check if there is any FC in the sample. If FC are present, there is a greater health risk because the sample recently has been exposed to feces and is more likely to contain pathogens. If there are no FC in the sample its assumed to be coliforms from the environment (ODW, 2016). The coliform group is used as an indicator of pollution for many reasons. Some key reasons are that coliforms is most likely present when pathogens are present, and because it generally stays alive longer than pathogens and the reduction of coliforms resembles pathogen reduction in water treatment solutions (National Research Council (U.S.) et al., 1977) (Havelaar et al., 2001). For litterature concerning the measurement procedure of coliforms, see Appendix A.

2.4.5 Health risks

Coliforms usually don't pose as a health risk but indicates the probability of other pathogens in the water. Coliforms may not be of fecal contamination which is a greater probability of pathogens but if testing is note done to exclude fecal contamination the water might pose as a health risk. Coliform testing is usually combined with E. coli testing to give further information of the pollution source and potential health risk.

2.4.6 Salmonella spp.

Salmonella spp. is an infective bacterium that causes illness. There are a multitude of different types of Salmonella spp. usually classified in serotypes. Serotypes are groups within a specific bacteria or virus which are distinguished by different parts of their shell structure. There are over 2500 different serotypes of Salmonella spp. but only about a hundred of them account for the majority of Salmonella spp. infections around the globe (CDC, 2019). Salmonella spp. can be found all around the globe and is able to survive several weeks in dry environments and several months in water (WHO, 2018b). Salmonella spp. originates from animal intestines and is transmitted through the animal's feces. Rainfall and runoff may carry Salmonella spp. through surface water to other water sources such as groundwater, drinking water or irrigation water sources. Salmonella spp. can survive harsh environments such as a lack of nutrients, ultraviolet radiation (UV) from the sun and changes in the pH (Liu et al., 2018). For litterature concerning the measurement procedure of Salmonella spp., see Appendix A.

2.4.7 Health risks

Salmonella spp. causes abdominal pain, fever, diarrhea, nausea and sometimes vomiting. The symptoms usually last between 4 to 7 days but sometimes results in longer or worse consequences. The Salmonella spp. bacteria are one of the four global key factors for diarrheal diseases (WHO, 2018b). The severity of Salmonella spp. sickness depends on the hosts sensitiveness and on the serotype of Salmonella spp.. Depending on the hosts age and immune system, different kinds of Salmonella spp. serotypes can be more threatening to the recipient's health and might cause long-term consequences or death (Braden, 2012) (WHO, 2018b). Generally old adults, children under the age of 5 or people with lowered immune systems are the most vulnerable to Salmonella spp. infections.

Table 1: Recommended microbiological guidelines for wastewater reuse set by WHO

Reuse Conditions	Exposed group	Feacal coliforms [cfu/ml]	Source
Irrigation of crops likely to be consumed uncooked, sport fields, public parks	Workers, consumers, public	≤ 1000	(Hesphanhol and Prost, 1994)

2.4.8 Chemical parameters

2.4.9 Biochemical Oxygen Demand

Dissolved oxygen (DO) refers to the certain concentration of oxygen being held by water. The DO is produced by plants and algae in the water via photosynthesis and by the water-atmosphere interface. DO is consumed by plants, algae, animals and bacteria in the water through respiration. Stagnant water is more likely to have lower DO levels due to the upper water level not moving resulting in less aeriation of the water body. Flowing water is constantly changing the upper water level resulting in more water being in contact with the atmosphere giving the water body higher DO levels. Higher water temperatures also lead to lower DO levels (Radwan et al., 2003). The biochemical oxygen demand (BOD) refers to the amount of oxygen consumed by bacteria and other organisms when they degrade organic matter in an aerobic waterbody at a specific temperature during a specific time. BOD tests are used to assess microbiological quality of wastewater.

BOD may not be the most significant parameter when evaluating irrigation water, but it is widely used as a parameter for evaluating wastewater treatment systems. If the BOD is reduced, one can assume that the amount of bacteria and other organisms also has been reduced.

2.4.10 Electrical Conductivity

Electrical conductivity (EC) is used to measure the number of ions in water. The more ions the higher the conductivity is measured. The water temperature also influences the conductivity. An increase in temperature results in a higher movability of ions which in return raises their conductivity. One of the most common set of ions in water is salt (NaCL) which is why EC is commonly used for measuring the salinity of water.

The accumulation of salt in the crop region is linked to loss of crop yield (Ayers and Westcot, 1994). The plants can no longer extract enough water when salinity is accumulated in the root zone. This results in a slower growing crop and sometimes results in the crop going through similar symptoms as when in drought. The salinity can enter through a water table not too deep from the roots or from irrigation water. The irrigation might also have a salinization effect on the water table beneath the plants, eventually resulting in a saline water table. When the water table is saline the salt will start to accumulate above the water table and eventually in the root zone.

2.4.11 Total, Volatile, and Fixed solids

Water can carry different organic and inorganic solid compounds. These solids have been correlated with an irrigation water system clogging and malfunctioning. Ayers and Westcot (1994) found that the accumulation of solids in irrigation systems and wells often lead to blocking of the water pathway. Solid particles in suspension has been pointed out as the leading cause to clogging of irrigation systems. When constructing and building a filter it is very important to know what rate of solids the filter can manage without clogging. Total solids (TS) is the solid residue of a sample after the liquid has been evaporated and later dried in an oven at 103-105 °C (EPA et al., 2001).

When samples of total solids are ignited, they lose weight through volatilization. The weight loss is measured as the parameter volatile solids (VS). According to EPA et al,. (2001) Volatile solids are often linked together with organic matter since they are ignitable and often attribute to a major part of the volatile solids. However, not only organic matter may be lost during ignition. Other matter may decompose or go through volatilization such as some sort of inorganic salts. The amount of solids left in a sample after ignition are called fixed solids (FS). The fixed solids are the part of the TS that is not lost during ignition. Hence, FS and VS are the two parts that make up the TS. There are correlations to be made for FS representing inorganic mineral matter and VS representing organic matter but as stated previously, this is not always the case.

Solids do not have a large impact on the plants themselves but tend to cause issues in irrigation water systems such as drip irrigation or in effluent streams or wells. Therefore, it is of importance to know the amount of TS in irrigation water when any treatment or irrigation watering system is to be applied.

2.4.12 Nitrogen and Phosphorus

Nitrogen is an essential macronutrient that increases the plants growth. Nitrogen might be naturally present in the soil or added with fertilizer. Nitrogen may also be present in the irrigation water and has the same effect as soil nitrogen. Too much nitrogen has a bad impact on plants and might lead to lesser plant quality, delayed maturity or less fruit production due to over-stimulation (Ayers and Westcot, 1994) (Hermanson et al., 2010). Excessive amounts of nitrogen in soils may have a negative impact on the environment and lead to acidic rain, gas emissions or eutrophication (Liu et al., 2014). Biochar has been shown to reduce nitrogen in irrigation water containing too high amounts of nitrogen (Feng et al., 2019)

Phosphorus is an essential macronutrient in the plants life cycle and is widely used in fertilizers around the globe. Phosphorus can be found naturally in organic compounds in the soil or in irrigation water. Excessive use of phosphorus fertilizer or naturally occurring abundance of phosphorus in water may result in eutrophication which has a negative impact on the environment (Torrent et al., 2007) (Li et al., 2018). The use of fertilizers containing phosphates might lead to chemical clogging of irrigation systems (Ayers and Westcot, 1994). For quality guideline values of Phosphorus and the other chemical parameters, see Table 2.

Table 2: Guidelines for interpretations of irrigation water quality set by FAO 1994. No restriction of use is assumed to benefit full production and capability of all crops. If values reach slight to moderate or severe values, some crops may not reach a good production and yield. A restriction of use does not mean that the water is unsuitable as irrigation water (Ayers and Westcot, 1994)

Parameter	Degree of restriction of use None	 Slight to moderate	 Severe	 Area of affect	 Source
EC [μS/cm]	<700	700-3000	>3000	Crop water availability	(Ayers and Westcot, 1994)
TS [mg/L]	<450	450-2000	>2000	Crop water availability	(Ayers and Westcot, 1994)
Nitrogen [mg/L]	<5	5-30	>30	Affects susceptible crops	(Ayers and Westcot, 1994)
pH		Normal range	6,5-8,4		(Ayers and Westcot, 1994)

3 Site selection and description of the study area

Small-scale wastewater treatments are in many cases designed for areas where there is a lack of communal responsibility, regarding a populations generated waste. The field work presented in this thesis was carried out in Kibera, the second largest slum in Africa, located in Nairobi. Here, around 200 to 700 thousand residents live together sharing tight quarters, without a regulated waste water treatment systems (Kimani-Murage and Ngindu, 2007). Choosing a proper placement in Kibera, for implementation of the charcoal vertical garden was an important part of the project.

The following sections of the paper will explain which factors affected the field site selection and later introduce the reader to some aspects of the settlement which are important, in order to fully understand the basis of the thesis. Much of the information presented in the sections were gathered by visual collection and local expertise. That is, by following the visual runoff, examine the urban terrain and by asking locals for information about their usual water and sanitation routines.

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3.1 Factors affecting site selection and placement of vertical garden

During the planned field work period a political election took part in the upper parts of Kibera, due to the unpredicted death of the current Kibera party leader. Elections are known to be inflammatory matters in Kibera as they have previously resulted in uprising of mobs along with forced military invasions from the state. Conducting a minor fields study in that situation was discouraged due to personal safety as well as for the protection of the charcoal filter. However, the Kibera settlement consists of 13 villages, one of which is Shilanga (Schouten and Mathenge, 2010). Since the village is in the lower parts of Kibera it was not included in the election district. It was for this reason that the Shilanga slum was decided as the field work zone. In other words, the charcoal vertical garden was to be placed, watered and tested somewhere within the boundaries of Shilanga.

When searching for an appropriate placement in Shilanga there were three main points to be followed. Firstly, the garden had to be safe from vandalizations and/or tampering from outer unknown disturbances, be that anything from freely roaming animals to curious local children. Secondly, it needed to be close to a reliable wastewater source to ease and enable a continues irrigation procedure. Lastly, the water source should be off suitable quality for filter treatment and have an incentive for purification. These three points were all considered when choosing the specific placement area in Shilanga.

A gated area within Shilanga was suggested as a future field site. The area is currently home to a small number of sheds, all accessible for local start-up businesses to utilise as they see fit, provided by the non-profit organisation GreenCard. Behind one of the sheds was a small garden, approximately 15 square meter in size and protected from trespassers by enclosing bushes on all sides. Since the compound itself is gated and the smaller garden was sheltered with vegetation, the site checked the first of the three points listed above, and was therefore considered a safe space for a filter placement.

A reliable drain-water source was located around 50 meters further down from the garden. Water could be collected from a small pond which was surrounded by a large amount of wetland, also known as the Nairobi Dam. The water surface area of the pond was always present and was known to expanded during heavy precipitation. The water source was considered a polluted, since its run-off area includes most parts of Kibera. Furthermore, the water from the pond was collected and re-used as irrigation water by local farmers. Considering these facts, the water source was deemed appropriate according to the second and third point stated in the beginning of the section. That is, the water source would be close enough to the filter to establish a working daily watering schedule and it was considered reliable and suited for filtering methods due to the regulation of the source and its origin. Most importantly, locals re-using the waste water as irrigation gave a further incentive for implementing a small-scale water treatment system in the area.

3.2 Nairobi Dam

The Nairobi dam was constructed in the early 1950´s and has a storage capacity and surface area of 98 000 m^3 and 350 000 m^2. The dam used to contain water but over the years the lack of regular maintenance has lead to an over-population of the common water hyacinth plant. As a result, most of the dam area was clogged. Today, the dam is considered to be a heavily silted wetland. The dam receives most of its run off from Kibera and Motoine River, and flows in to Ngong river, which eventually leads to Nairobi river (Rugo, 2015).

As of today, local opportunists have reclaimed much of the wetland area for agriculture. Locals are not only farming on top of the wetland, but they are also gathering water from the source to irrigate other produces located upstream. They are collecting water from a pond, the same collection point that was selected as a water source for this project, and are providing water for three larger horizontal fields growing tomatoes, kale and spinach. The water is collected by hand using buckets and/or a water pitcher and is distributed across the fields. The crops are later harvested and sold as greens to others in the community.

The quality of the water source becomes important when it is re-used as irrigation, especially when considering health concerns for crop consumers and the farmers themselves. The study gave an opportunity to examine the quality of the water whilst evaluating the performance of a charcoal vertical garden on the water used as irrigation.

3.3 Sanitation and water handling

Main roads in Kibera have been provided with superficial water pipe lines. The water pipes are providing outlets of water taps which can provide locals with fresh water. However, the water is not a free-for-all concept. Someone needs to pay for the water to be served, consequently turning drinking water tap-ups in to lucrative businesses (Kimani-Murage and Ngindu, 2007). However, the price of tap water is based on the market value and is therefore prone to vary. Once the water has been brought home to a resident, the water is used for drinking, cooking, cleaning and washing throughout the day. How much a household uses varies depending on family structures. According to Pardo Ule Mmoja, a resident at Kibera and assistant to the project, a family of three uses around 30-40 litres every day (2018). The water is re-used for household purposes until deemed too dirty to use again. The wastewater then gets dispersed out on to the street flowing in to one of the street drenches, see Figure 3.

The drenches are usually dug in the soil or constructed from concrete and are spread like a web throughout Kibera. The drenches drain the greywater released every day and works as a river for precipitation and run-off in the area. In some places, smaller drenches meet and merge in to bigger canals. There is usually always some water running, most of which is the result from wastewater disposal by the community and/or precipitation flowing down from higher altitudes.

Regarding sustainable sanitary facilities, there are public latrines installed in the Kibera area. However, due to the high user load the latrines can quickly get overfilled with waste. Emptying latrines can be done by machine or by hand, both of which costs money for the community. Therefore, a lot of the latrines get emptied into the drenches. Over-filled latrines are unpleasant for people to use and as a consequence some prefer to fulfil their needs in the open, usually in a smaller hidden wastewater canal. Also, latrines charge for single use which further promotes open defecation. Some households are so close to drenches that they can have private parts of the shed, dedicated for waste, which is directly emptied down into the drenches, see Figure 3.

The mesh drenches system is a positive attribute during rainy season, as it can help lead away bigger water volumes from the streets. However, this results in large volumes of wastewater and fecal contamination reaching the Nairobi dam. There is no sanitation treatment for the waste dispersed in Kibera and the canals pass through the heavily over-flooded latrines, mixing it in to the river and leading it down towards the dam.

Figure 3: Two drenches eminating out of Kibera to the Nairobi Dam. A household excreta drainage can be seen pouring directly in to the wastewater drench on the picture to the left. Authors' photo.

3.4 Food security

In crowded settlements like that of Kibera, there is a need for creativity and solution-oriented ideas. The high population status of the community increases the need for employment. Most locals in Kibera make their living working in the city centre, working for example as cookers, cleaners or security guards. However, there are ways of making money in Kibera itself, and many locals are entrepreneurs with their own shops/stands offering everything from cooked food and vegetables to custom-made clothes.

Locals spend most of their money on water and food, both of which are prone to vary greatly in pricing, depending on quality and competitiveness from other salesmen. Food security is low in Kibera where people are more inclined to buy bigger quantity of lower quality vegetables rather than spending their money on lesser, but fresher, crops. This makes the price of food a contributor of potential health risk.

Common vegetables sold in Kibera are the leaf vegetables spinach and kale as well as tomatoes, avocados and potatoes. There is a clear advantage for people who can grow their own crops. Not only can a source of produce be a way of making money, but when prices for vegetables peak on the street, there is another source of food available at home. The living situation in Kibera is crowded and there is no space for growing vegetable in the traditional sense. That is why people have started to move towards different types of urban gardening. In Kibera the vertical garden has been established as a functioning way generating high yield crops on a limited space. The owner fills a weave bag with soil found in the area and makes small holes around the bag. The holes and top of the vertical garden are filled with seeds or seedlings and usually watered with re-used water from home, also known as greywater, as this is easy to come by.

4 Design of vertical garden

The design and construction of the vertical garden was based on the information gathered during the choice of field-site and the knowledge of the water source quality. The design of the vertical garden was carefully planned and drawn within a week of choosing the field-site. The procedure of designing the charcoal vertical garden is laid out in the following section.

4.1 Design criteras

The design of the vertical garden had a few criterias listed below. Some of criterias were based on the idea that the vertical garden should be a low-cost and easy investment for anyone to reproduce. Whilst other criteria focus on the functionality of the vertical garden as a treatment filter.

1. Easy to construct
2. Accessible materials
3. Materials that needs to be purchased should be as budget friendly as possible
4. Environmentally sustainable
5. Produce as high crop yield as possible
6. Have a sanitary effect on influent water
7. Avoid crops getting contaminated by the irrigation water
8. Have a controlled hydraulic loading rate
9. Easy to collect effluent water while not promoting stagnation of water volume in the bottom of the garden.
10. Minimal clogging of system.
11. Maximal sanitary results on effluent water.

4.2 Bodyframe of vertical garden

For the frame of the vertical garden a gunny bag (polypropylene) was picked as the main body, see Figure 4 part B. The bag is commonly used in Kenya for storage and transportation of anything from grains to charcoal, making it a free and accessible material.

The gunny bag picked for the garden was free from holes and was 107 cm in long and 60 cm wide. After the bag had been filled with filter material it measured at 35 cm in diameter and 82 cm in height. Re-using a gunny bag was an environmental positive choice.

4.3 Biochar grain size

The biochar used as the filter medium was bought from a local vendor. The biochar was to be crushed into two different sizes, one for the top and bottom layer, and one for the middle part of the sack. The top and bottom layers were designed to be of larger charcoal pieces (4-12 mm)to promote drainage and avoid clogging. The middle layer was designed to be of smaller grain size to promote treatment. The top and bottom layer were designed to only be 10 cm each while the middle part makes up the majority of the sack volume.

Crushing charcoal in to one definite size was hard to guarantee. Instead, the main size was decided as a range between 1,7 and 4 mm. The smaller grain size was based on literature and the knowledge regarding the water source quality. These grain sizes were chosen to promote design criteria 10 and 11. The two grain size ranges were obtained by crushing charcoal and sieving it to collect the chosen size.

4.4 Soil cups for planting

In order to promote design criteria 1-5, the design included reusing material such as plastic bottles to make soil cups. The entire garden was designed to contain 25 cups. They were to be placed around each other throughout the filter, to create a homogeneous water-flow to promote each plant getting access to the irrigation water. It was also decided that the plastic bottles should be punctured with 2-3 mm holes to further insure that the plant would get access to water. Re-using plastic and collecting materials of the street is environmentally positive. It is also cheap, and easily accessible in many parts of Kenya.

4.5 Choice of crop

Due to the design of the garden the crop used should be easy to grow, light weighted and commonly used by the locals. Both spinach and cabbage would work according to the design. Due to availability at the time, spinach became the chosen crop. What is referred to as spinach in Kenya is actually Swiss Chard but has been translated to English as spinach. According to locals, the spinach should take 3-4 weeks to grow to full size if given an optimum environment. The crops could reach, approximately, 30 cm around harvest time. It was decided to grow one seedling for each cup, making it 25 seedlings in total.

4.6 Bottom base of vertical garden

The bottom base of this filter was designed to promote design criteria 9, 10. That is, to construct a design which would generate an easy water flow collection and minimising water-detainment while also preventing the bottom part of the bag from clogging.

The basin of the vertical garden was designed as a plastic wash basin with a bottom diameter greater than the diameter of the filled weave bag, 35 cm. The upper part of the basin could be cut off, giving the basin a height of around 20 cm. The bottom basin was also designed to have a tap to easily collect the effluent water See Figure 4, part D.

To maximise the water flow and minimise the water-detainment in the basin, a small wooden construction was placed between the bottom of the charcoal sack and the basin bottom to promote drainage See Figure 4, part C.

4.7 Top part of charcoal vertical garden

The top part of the vertical garden was first and foremost designed to promote criteria 5, 7 and 8. It consists of a basin with a bottom diameter as big as the vertical garden and made with holes spread across the bottom, see Figure 4 part A. The basin is designed to be used in two ways, for several reasons:

1. For every time the garden is going to be watered the basin should be placed with the bottom down towards the biochar.
   - The holes help to spread the incoming water evenly across the surface area
   - Controls a constant flow.
   - The high walls of the basin serves as a splash protection for the planted crops, minimising pathogen contamination of the plants.
2. All other times the basin should be placed as a hat on top of the garden with a small plywood covering the holes with a rock to ensure that the cover stays in place.
   - This protects the biochar from getting affected by heavy rainfalls without covering the plants from any sun exposure.
   - Allows the plant to retrieve water from the rain fall without having it affect the charcoal.
   - Minimises water lost to evaporation from soil surface area
   - Protects the sample water inside the filter from being affected by rainwater. This is relevant for the sake of the study, but would not presumably be an issue in everyday use.

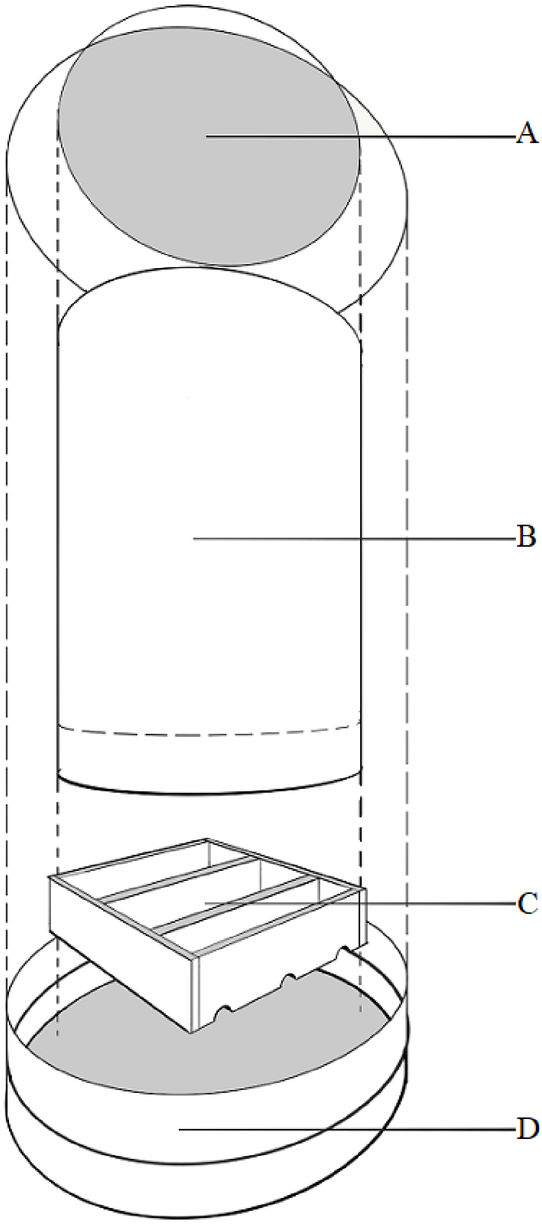

Figure 4: Sketch of the vertical garden. A= Top basin, B=The charcoal filled sack, C= Wooden drainage construct, D= Bottom basin with effluent tap. Authors figure.

4.8 Soil collection

The soil was collected on a field inside the Nairobi University department of agriculture and veterinary science campus. The field had belonged to the university for a long time. According to Dr. Nduihu Gitahi, the grass covered plane had been used for cattle grazing in the past and was considered to be naturally fertilized by the grazing animals. Around 80 litres were retrieved and collected in weave bags.

4.9 Charcoal collection

Since the quality and composition of the charcoal influences the sanitary effect of irrigation water, it was important to get as much information about its origin as possible. One charcoal bag with mixed sizes was purchased by a local business. According to the vendor, the charcoal was approximately 2 weeks old. The business owner buys the charcoal in bigger quantity from the market spaces and then sorts it in to appropriate sizes before selling them per 5 litre bucket. The bigger size are considered better charcoal for cooking and are sold to locals as fuel. The dust and smallest grain sizes are cast aside and is not currently used for anything or sold by the vendor.

The charcoal manufacturer chooses the hardest tree they can find, as this will give a higher charcoal to ash ratio. It is typical to cut and use the wood from the acacia trees for making charcoal and this is what the vendor believes our purchased charcoal steams from. The charcoal was made with as little oxygen present as possible. First the hard wood was cut in to long logs and put on piles on the ground. These piles were then first covered with grass and later with sand. The grass functioned to protect the sand from infiltrating the log piles and putting out the fire. During pyrolysis, one side of the pile was open to air, which is where the fire was lit. Even though the pile was covered with sand, it contained tiny air holes which helped the fire not to burn out. However, the presence of oxygen was small enough to keep the wood red-hot without catching on fire, as this would have lead to creating ash. The procedure could take anywhere from 1-3 weeks depending on the size of the pile created.

5 Method/Methodology

The method section will be divided in to three periods. The first period extended over three weeks. This was the start of the project after arriving in Nairobi. During period 1 a suitable project field site was chosen and the vertical garden was designed and constructed. At the end of period 1, the filter characteristics were tested.

Period 2 entails the majority of laboratory work conducted during the thesis. The period starts after the filter has been placed at its location in Shilanga and continues for a 5 week sampling period. During the first four weeks samples were collected from the garden twice weekly but only one sample was collected for on-site analyses during the fifth and final week. Microbiology, chemical and biological analyses were conducted during this period. During week 5, samples of influent and effluent water were collected in falcon tubes everyday for 7 days. These samples were collected to be taken back home to Sweden for further testing, during period 3.

The third and final period started when the sampling period was over and it was time to collected and analyse some of generated spinach crop. The spinach was brought back to the lab and tested for contamination through microbiology analyses and generated spinach yield. This period also includes the analyses performed on the samples collected every day during week 5. These analyses were conducted at SLU after the samples had been brought back to Sweden.

5.1 Period 1: Construction and testing of filter characteristics

During this period, the charcoal vertical garden was constructed and its porosity, pore volume and water holding capacity were all measured before plantation of spinach and commence of operation.

5.2 Preparation of Charcoal

Throughout the process, three different techniques have been applied to obtain suitable grain sizes for sorting:

1. Crushing charcoal between two rocks until appropriate size
2. Bundling a bigger amount of charcoal in double layered weave bag and then using a rod to beat the bag on the ground until the charcoal obtained the right size
3. Putting charcoal in a bigger metal bucket and then using a rod with a wider bottom part to crush and grind the charcoal into smaller pieces

The residue of the charcoal chopping was then transferred to a basket with a net hole size of 12 mm and shaken until all sizes bigger than 12 mm were removed. The charcoal that passed through the basket was transferred to a sieve with a hole size of 4 mm. The sieve was built on-site using a hens-net and four pieces of wood for a frame. The charcoal that got stuck in the hens-net was separated into a container designated for the bottom and the top part of the garden.

Finally, a smaller 1,7 mm metal sieve was used to strain away smaller pieces of dust. Charcoal which got stuck on the smaller sieve was gathered in another container, for the main body of the vertical garden with a grain size between 1,7 and 4 mm, see Figure 5.

Figure 5: Sievs used to separating charcoal: 13 mm basket (left), 4 mm (middle) and 1,7 mm (right). Authors' pictures.

5.3 Constructing the vertical garden

5.3.1 Procedure

A 100 L (polypropylene) gunny bag was filled with a 10 cm layer of 4-12 mm charcoal, followed by a 5 cm layer of the smaller grain size (1,7-4 mm).

A total of 15 PET (polyethylene terephthalate) bottles were cut in two with a small scalpel and multiple holes (2-3 mm) were made with a sharpened nail throughout the bottles. All of the half bottles were filled with the collected soil. Five of the half bottles were moved to the gunny bag and placed in a circle on top of the charcoal layers, see Figure 6. After every row of cups were placed they were covered with a layer of the smaller charcoal grains and the cup location was marked outside on the weave bag with a marker pen.

Every new row of cups was shifted one step to the right from the previous row. In total the garden contained six rows. After all the cups had been placed, a 10 cm layer of bigger charcoal grains was distributed on top of the filter.

Figure 6: Plastic bottles filled with soil (right) and bottles placed inside filter gunny bag. Authors' pictures

The base of the vertical garden was created using a base of a HDPE (High-density polyethylene) plastic basin (35 cm diameter and 20 cm height). On the bottom of the basin a small hole (2 cm) was made using an iron rod which had been heated in a fire and a plastic tube was pushed into the hole. The tube was then welded into place by the heated steel rod. To construct the drainage in the basin bottom two pieces of wood the exact size of the basin diameter was cut out of a wooden plank with a saw. A total of three smaller pieces of wood were laid between the two longer strips see Figure 7.

A second basin (same material and size as the bottom basin) was punctured with a sharp tool, creating small holes (2-3 mm) systematically spread across its bottom and placed on top of the gunny bag, see Figures 7 & 8. The charcoal filled sack was then lifted into the bottom basin. At last, a bigger plastic bag was wrapped around the bottom basin and the filter, covering the gap between the basin and the bag. The plastic was set by tying two rubber bands at the upper and lower end of the bag see Figure 8.

Figure 7: Bottom part of VG with wooden cuttings showing in the base (left) and top part of the garden, showing the flow after being poured with 4 litres of water (right). Authors' picture

Figure 8: The finished vertical garden before spinach seedlings were planted. Authors picture.

5.4 Washing of the Charcoal filter

After the construction of the garden it needed to be flushed properly. Access to water on Campus grounds were limited but in total 120 litre was collected in tanks of 20 litre each. A bigger trash can with a volume of 50 litres was filled to the brim with tap water. To maximise the flushing effect of the garden it was lifted out of its bottom container and placed on top of two big concrete stones which were placed 30 cm apart from each other. This ensures a free flow from as much of the bottom part of the garden as possible.

Four sponges were put on top of the gardens surface area to maximise a homogeneous spread of water as well as minimizing any impact caused by a direct water flow. The vertical garden was flushed with 120 litre water for 31 minutes using 1 litre bottles. Approximately 2-3 of the one litre bottles were filled in the bucket and distributed on to the sponges every minute.

5.5 Hydraulic residence time and tracer analyses

The hydraulic residence time was determined on the filter by adding a pulse of specific conductivity and analysing its interaction with the filter while providing the garden with the a HLR set to around 120 L/m2/day for 2,5 days.

Salt (842,2 mg of NaCl) was added to a glass of 200 ml distilled water until the EC reached 3454 μS. The tracer puls was then added to the vertical garden along with 4L of tap water as part of a HLR. Four liters of water were added three times a day at 8:00, 12:00, and 16:00 to mimic the same HLR the garden would have in Kibera. A bucket was placed beneath the effluent tap of the garden to collect all effluent water. As soon as the bucket had 200 mL of water, the EC was measured. The bucket was then emptied and rinsed and put back at the effluent tap to keep collecting water. The measuring and emptying of the bucket only took place between 8:00 and 17:00 due to campus closing times. During the night the effluent was not measured. The mean gathered from the three first measurements conducted after the pulse was added, 1200 μS, was considered the background conductivity.

The breakthrough curve and retention time of the filter was then determined by converting conductivity measurements into mg/l and multiplying these with the volume collected during every measurement. Prior to this, the background conductivity was subtracted from the measured values. The pulse conductivity was also converted to mg/l and multiplied with the amount added to the filter, 200ml.The subtracted conductivity measurements were accumulated for every new measurement and divided by the pulse conductivity and plotted in a graph over time. The retention time was retrieved from the graph at the 0.5 y-axis value.

5.6 Period 2: Initial performance of charcoal vertical garden

Period 2 started after the vertical garden was placed in Shilanga and operated in wastewater treatment. This period extended over 5 weeks. At the beginning of period 2 a hydraulic loading rate had been decided and implemented for 5 days prior to the first water collection and the spinach seedlings were planted in the beginning of the first week, see Figure 9.

Figure 9: Spinach seedling being planted in the soil filled cups on the first day of week 1, period 2. Authors' picture.

The main focus during this period was to assess the performance of the garden and to analyse the quality of in and effluent water from the garden. This was done by analysing the collected samples for Salmonella spp., E.coli, and coliforms as well as determining the BOD, TS, VS, FS, EC, and pH. Samples were collected in Shilanga twice a week for 4 weeks and once at the beginning of week 5. During the last week samples were collected every day for 7 days and prepared to be brought back to Sweden for further testing. See Figure 32 for an example schedule of sampling during period 2.

5.6.1 Analyses of microbial, physical and biological water quality

5.6.2 E. Coli, Coliform and Salmonella spp.

A series dilutions of 1/10, 1/100 and 1/1000 were preapared and the Fecal coliforms, E.Coli and Salmonella spp. were analysed in these dilutions. Also, duplicates of a zero-diluted sample were always prepared.

Collected water samples was gathered and prepared for testing within four hours after collection in Shilanga. Water samples were kept in a cooler bag during transport from Kibera to the Nairobi University. All samples were left 10-15 minutes to condition to room temperature before the microbiology analysis.

Before starting any analysis, a sterile working space was created by wiping tables and equipment with disinfectant detergent and igniting a bunson burner next to the work space. To minimize chances of sample or plate contamination strictly sterile equipment was used within the prepared sterile area. Cross-contamination between samples was avoided by always changing pipettes and L-shaped spreader for every new agar plate.

The first testing tube was filled with 10 ml of chosen water sample and vortexed thoroughly. Three other test tubes were filled with 9 ml of the prepared 1 Mm NaCl dilution and marked as -1, -2 and -3. With a millilitre-pipett 1 ml was collected from the middle of test tube 0 and transferred to tube -1 and vortexed. With a new pipette, 1 ml was collected from the middle of test tube -1 and transferred to test tube -2. The diluted sample was vortexed and once again 1 ml of the sample was collected and transferred to the last tube marked as -3, see Figure 10.

For analyses of Salmonella spp., a volume of 1 mL was transferred from each tube in dilutions series and spread on XLD plate (SVA, Uppsala, Sweden). For XLD plating, Using a scraping motion and L-shaped spreader, the samples was distributed across the plate. For analyses of E. coli and coliform , a volume of 100 µL was spread on Chromocult plates (VWR, Stockholm, Sweden). The plates were flipped up-side down and set to rest for approximately 10-15 minutes before being transferred to an incubator set at 37°C. The plates were incubated for 24 hours. After 24 hours the formed bacterial colonies were counted. For the Chromocult plates, clear red colonies represented fecal coliforms and dark blue/purple growths indicates E. coli. For the XLD plates, black colonies represented Salmonella spp. and all colonies were counted.

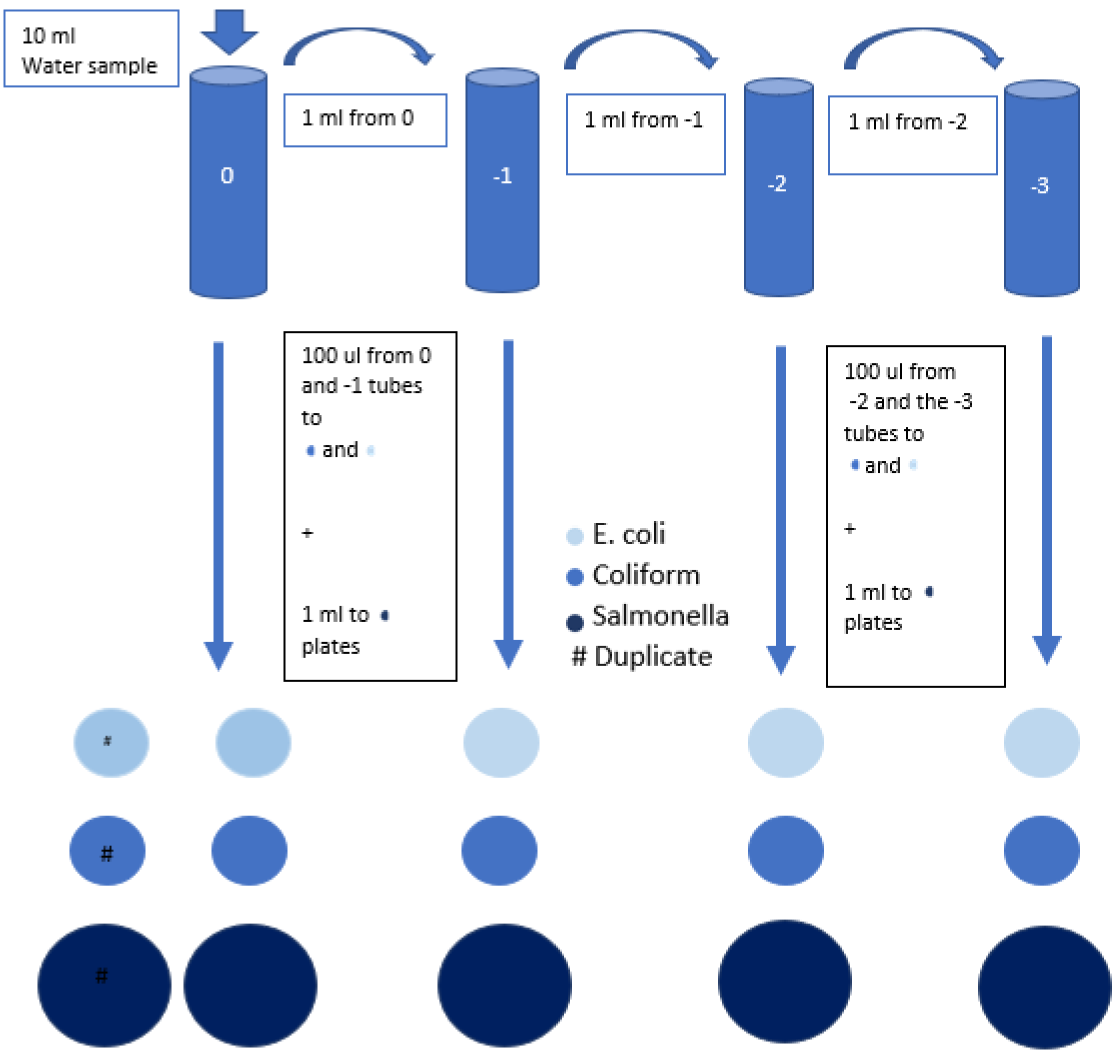

Figure 10: Dilution example procedure

5.6.3 Triple sugar iron (TSI) testing

Triple Sugar Iron (TSI) test was used as a first step in distinguishing Salmonella spp. from Proteus. The Urease broth test is the second step to accurately determine presence of Salmonella spp..

TSI agar contains three types of sugar, Lactose, Sucrose, and Glucose. Depending on which sugars the sample ferment, the TSI will show different colors and growths. Some organisms are able to produce different gases which yields bubbles in the agar and helps when determining the specific organisms. The TSI agar are placed in test tube which are slanted so that the test tubes contain a bottom part with no available oxygen and a top slope with oxygen. Salmonella spp. will produce a yellow bottom with a red top slope and might produce gas bubbles and black growth depending on which type of Salmonella spp. is present in the sample. Some types of Proteus will result in similar results as Salmonella spp. while other types will result in a yellow bottom and slope.

The workspace was disinfected according to aforementioned described procedure. The colonies of interest where extracted from the XLD plates using a plastic stick. Colonies of different sizes surrounded by different pH were chosen to catch a broad spectrum of colonies. The plastic stick was then put in the corresponding TSI test tube and spread on the bottom and the slope. The test tubes caps were loosely placed on the top of the tubes to allow oxygen to pass. The test tubes were then placed in an incubator at 35-37°C for 24 hours before the results where read.

5.6.4 Urease broth Test

The test is conducted as a final step to determine if growths from TSI tests are Salmonella spp. or proteus.

The urease test checks an organism's ability to dissolve urea. When urea is dissolved, ammonium and carbon dioxide is created as a biproduct. The ammonium makes the urea agar alkaline and it switches colour to magenta. If the organism is not able to dissolve urea this reaction does not occur and no pH changes occur, leaving the agar colour unchanged. Proteus has the ability to dissolve urea while Salmonella spp. does not. The urea agar containers are kept tilted when the agar is cooled so that they have both a bottom layer and a slope.

Each urea agar container was individually marked with a marking correlating it to its TSI test tube. The workspace was disinfected, and a gas torch was used to minimize air contamination. Colonies from the TSI test tubes were extracted with a plastic stick to the bottom and slope part of the urea agar (Nairobi University, Nairobi, Kenya). The urea containers where then incubated for 24 hours at 35-37°C before the results were read from its final color.

5.6.5 Soil examined for Salmonella spp.

The soil used for growing spinach in the vertical garden was inspected for the presence of Salmonella spp. contamination. A 5 g of sample soil was weighed and transferred to 45 ml of buffered peptone water. This mixture was incubated for 24 hours at 37°C. Three duplicates were prepared.

After incubation time, 1 ml of the activated soil samples was transferred to 9 ml of RVS broth for cultivating Salmonella spp. species. The samples then incubated for 24 hours at 37°C and later spread, undiluted, on to XLD plates.

The XLD plates were incubated for 24 hours and then read for Salmonella spp..

5.6.6 Biochemical Oxygen Demand

BOD was measured to give an overall assessment of the vertical gardens filtering abilities. The BOD measurements were conducted once a week at the start of Period 2 and twice a week at the end of week 4, see Figure 32.

Nine individually marked 300mL BOD bottles were used to perform the BOD test. Each Bottle was filled with a sample volume and diluted with distilled water. Some samples were not diluted. Eight individually marked batches of approximately 3mg nitrification inhibitor TCMP - 2-chloro-6 (trichloromethyl) pyridine (N-Serve) were prepared using an analytical scale. The sample and distilled water was added to the BOD bottles using a wide mouth pipette pouring the water on the inner side of the top glass cylinder to avoid entrapping air. When the sample or dilution volume reached 2/3rds of the bottle volume, the nitrification inhibitor TCMP was added to the bottle. The bottles where then continuously filled up using a wide mouth pipette to the 300-ml mark at the "neck" of the bottles. The blank sample bottle was filled with distilled water and did not contain any TCMP.

The DO-meter was set up according to the manual for DO measurements and calibrated using the air-calibration method. The DO-meter was then used to measure the initial DO levels of each BOD bottle. The DO-probe was cleansed with distilled water and wiped dry with Kimtech wipes between every measurement. Once the initial DO was measure, the BOD bottles were plugged shut with their respective glass stopper. Each BOD bottle was then thoroughly checked for air bubbles to make sure no visible bubbles of air were entrapped in the bottles. The top cylinder part was then filled with distilled water to make sure no air could pass through the stopper to contaminate the sample. Once the BOD bottles were checked they were put in the incubator at 20±2°C for five days.

After 5 days of incubation, each bottle was removed from the incubator for the final DO measurement. The top cylinder part was emptied of distilled water before the glass stoppers were removed. The DO-meter was calibrated using the air-calibration method and then used to measure the final DO level of each bottle. The DO-probe was rinsed with distilled water and wiped dry with Kimtech wipes between every measurement. The final BOD was calculated using the following equation:

$$BOD_5\,[mg/L] = \frac{(D_1 - D_2)}{P} \tag{1}$$

Where: D_1=DO of diluted or undiluted sample after preparation, mg/L. D_2=DO of diluted sample after 5 days of incubation at 20± 20°C, mg/L. P= the decimal volumetric fraction of sample used.

5.6.7 Solids

5.6.8 Total Solids

The evaporation dishes were rinsed and disinfected in the furnace at 550°C for 1 hour. The dishes were then placed in a desiccator to reach room temperature. Each dish was then weighed on an analytical scale. The samples were put in a glass beaker and stirred using a magnetic stirrer. The sample volume for the dishes was collected from the glass beaker while is was stirring. Using a wide mouth pipette the selected sample volume was collected halfway down in the stirred sample next to the vortex. The dishes were then placed in the drying oven at 98°C as well as the blank sample dish which did not contain any sample. Once the fluids were evaporated, the temperature was raised to 103-105°C for drying. After 1 hour the dishes were extracted from the oven and cooled in a desiccator. Each dish was then weighed using an analytical scale and placed back in the oven. The drying (103-105°C) for 1 hour and weighing procedure was repeated until the weight stabilized. The final weight was then written down and used to calculate the total solids [mg/L] using the following equation:

$$TS\,[mg/L] = \frac{(A-B)\times 1000}{sample\,volume,\,mL} \tag{2}$$

Where: A= weight of the dried residue + dish, mg. B= weight of dish, mg.

5.6.9 Volatile Solids Procedure

Once the final total solids weight was obtained, each dish was placed in a furnace at 550°C for 15 minutes. The samples were then extracted from the furnace and placed in a desiccator to cool off. Once the dishes reached room temperature, they were weighed using an analytical scale. The samples were then placed back in the furnace for further ignition and the procedure was repeated until the weight had stabilized. The final weight was written down and used to calculate the volatile solids [mg/L] using the following equation:

$$VS\,[mg/L] = \frac{(A-B)\times 1000}{sample\,volume,\,ml} \tag{3}$$

Where: A= weight of the residue + dish before ignition, mg. B= weight of residue + dish after ignition, mg.

5.6.10 Fixed Solids

The fixed solids weight was calculated as the difference between total solids and volatile solids for each dish using the following equation:

$$FS\,[mg/L] = \frac{(B-C)\times 1000}{sample\,volume,\,ml} \tag{4}$$

Where: B= weight of residue + dish after ignition, mg. C= weight of dish, mg.

5.7 Period 3

Period three includes the final stage of the field work. At this point the sampling of water sources was finished and it was time to collect some of the spinach crop for harvest to be analysed for traces of contamination as well as for determining the spinach yielded by the garden.

The samples which had been collected in falcon tubes every day during the last week of period 2 contained one drop of Hydrochloric Acid (HCL), giving the samples a pH around 2,3 and fixing the organics and nutrients from the water source. The samples were later kept in room temperature one month before the analyses began again, this time in Sweden. Back at the SLU laboratory, the samples were analysed for COD, tot-N and tot-P. The samples dry matter and amount of volatile solids were also determined.

5.7.1 Spinach analyses

The vertical garden was divided in to three zones (lower, middle and upper). Three random leaves were picked from each zone and brought back to the University for testing. Firstly, all plants were measured with a ruler and the yield was estimated through comparisons with the measurements taken during period 1.

Secondly, all excessive soil at the end of the root was cleaned of with a sterile brush. Each leaf was then put in to their own stomacher bag and 1, 2 and 3 ml of solution was added for each of the three leaves bag of each zone. One by one the bags were placed in the stomacher and beaten for 2 minutes.

The mixed solution in the bottom of the bag was collected using a pipette and transferred on to XLD and chromocult agar plates. The plates were spread using an L-shaped spreader and placed upside down in an incubator at 37°C. After 24 hours, the plates were removed from incubator and screened for countable units of E.coli, Coliforms and Salmonella spp.

5.7.2 Tot-P, Tot-N and COD

The influent and effluent water samples collected during everyday of week 5, period 2, were analysed to determine the COD, Tot-N and Tot-P using Spectroquant® cell kits number 14772-14773 for COD, 114687cell 14848 for Tot/P, and crack set 20 and kit 14963 for To-N (Merck KGaA, Darmstadt, Germany)

6 Results

6.1 Influent water quality and characteristics

The results from the influent water samples showed that the water quality varied depending on weather and wastewater runoff from Kibera, see Table 3. E. coli was the parameter most affected by weather. For a visual comparison of the sample collection point at stable weather conditions and after heavy rain and runoff see Figure 33, in Appendix D.

Table 3: Results from inluent water samples showcasing the quality and characteristics of the current irrigation water. *=Maximum and minimum values from heavy rainfall periods. Mean values are calculated from the total data with no regard to weather conditions. The guideline values are taken from Table 1 and 2, for references and further guideline values see each table. Degree of restriction of use is set from the total mean value of the specified parameter. [1]=Degree of restriction on use varies depending on weather conditions. (n)=Number of observations.

	E. coli [cfu/ml]	Coliforms [cfu/ml]	Salmonella spp. [cfu/ml]	TS [mg/L]	pH	EC [μS/cm]	Tot-N [mg/L]	Tot-P [mg/L]	COD [mg/L]	BOD_5 [mg/L]
Mean	1357	25758	1,7	1060,6	7,3	1546,6	20	1,07	590,9	7,9
Maximum	$12{\cdot}10^3$*	$10{,}3{\cdot}10^4$*	10	3210	7,66	1936	43	1,74	1218	14,8
Minimum	20	3300	0	420	6,95	766*	8,6	0,5	198	4,1
(n)	16	13	13	17	7	7	7	7	7	5
Quality Guideline	≤1000 see Table 1	-	-	<450 see Table 2	6,5-8,4 see Table 2	<700 see Table 2	<5 see Table 2	-	-	-
Degree of restriction on use	Not suitable[1]			Slight to moderate	None	Slight to moderate	Slight to moderate			

6.2 Filter Efficiency

The pH increased from a mean pH of 7,3 in the influent to a mean pH of 8,2 in the effluent when passing through the vertical garden, see Figure 11.

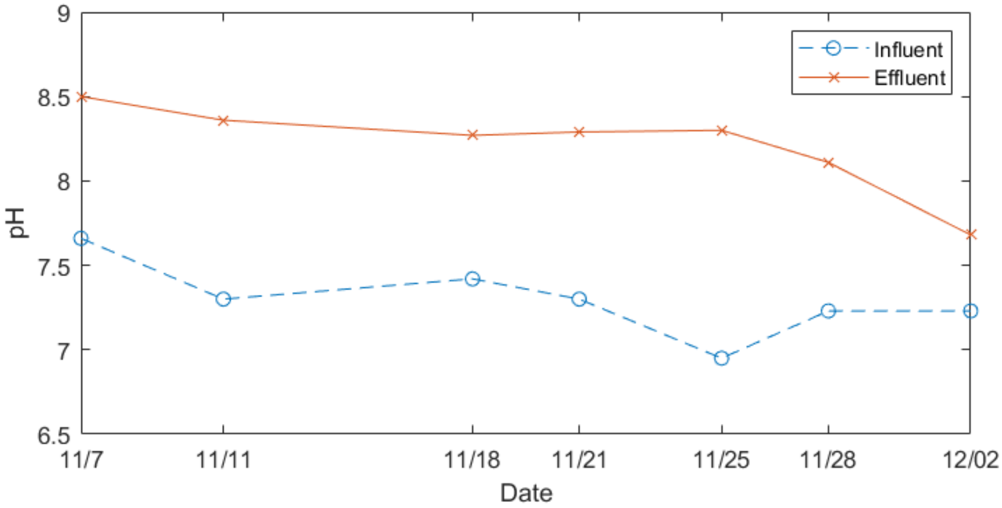

Figure 11: PH levels of effluent and influent water during the sampling period.

The EC decreased from a mean value of 1546 μS/cm to 1396 μS/cm when passing throuh the vertical garden. The EC decreased significantly on two occasions, November 25th and December 2nd, see Figure 12. Both these dates were impacted by heavy rains and runoff.

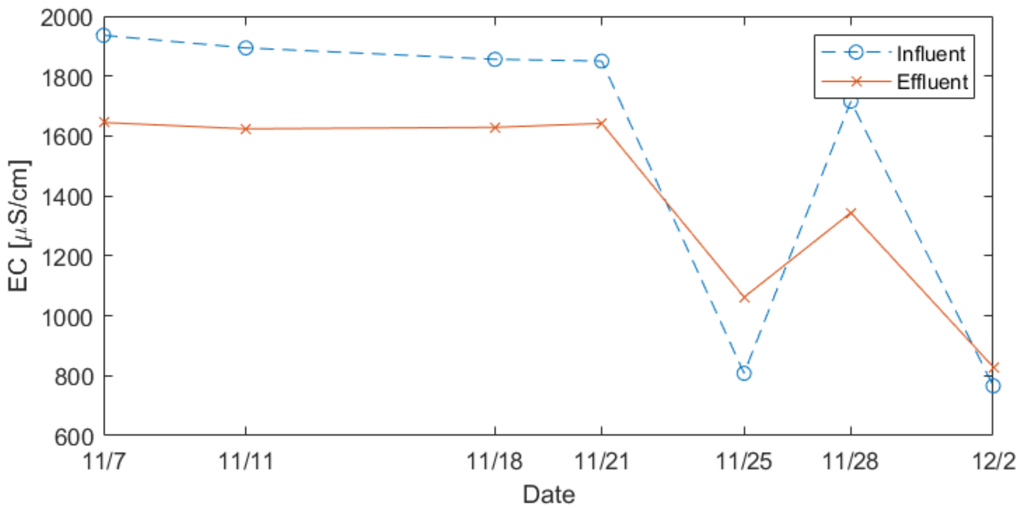

Figure 12: EC levels of effluent and influent water during the sampling period.

6.2.1 E. coli

The influent median of E. coli was 70 cfu/ml, calculated using all the collected data. E. coli increased significantly on November 25th and December 2nd, see Figure 13. Both these dates were influenced by heavy rainfall and increased runoff from Kibera. The total E. coli results show a clear reduction of E. coli when the water passed through the filter. The total mean reduction of E. coli was 77,7%, see Table 4. Mean values and average reduction for total-, increased runoff-, and stable weather E. coli are shown in Table 4.

The quality data range set for E. coli was 30-300 countable colonies per plate. Hence, dilutions containing less than 30 colonies or above 300 colonies were considered either too diluted or not diluted enough. The results showing 0 colonies are all from undiluted samples which are a true representation of E. coli presence and therefore considered valid.

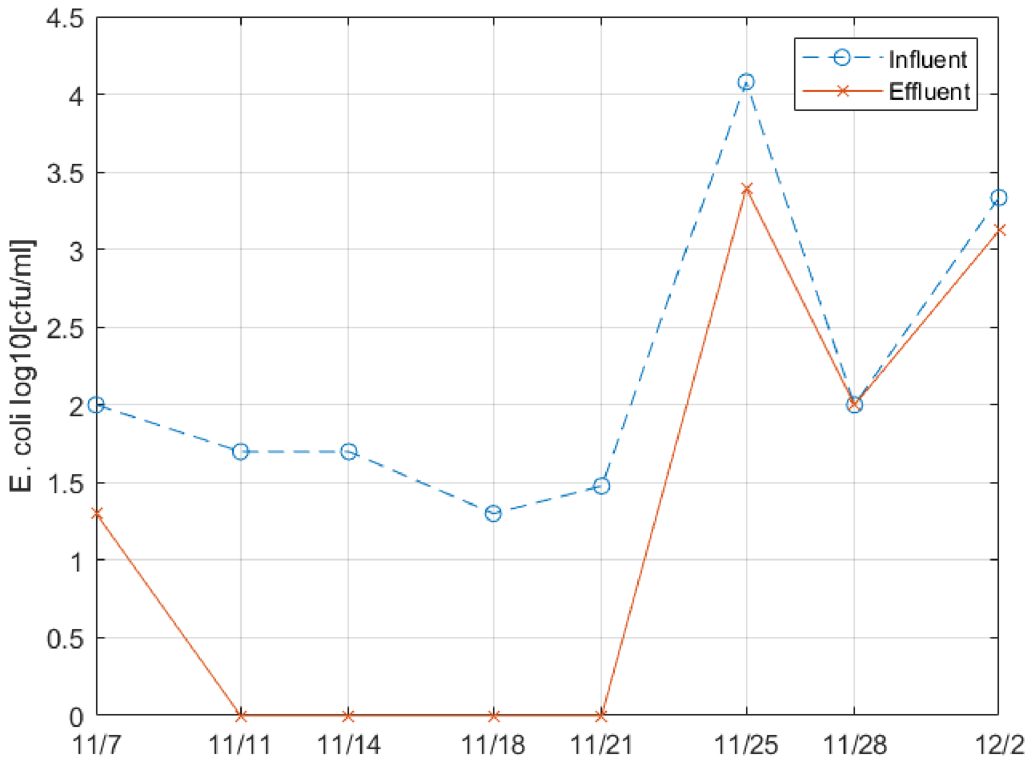

Figure 13: Concentrations of E. coli (cfu/ml) during the sampling period. Multiple plates were tested for each sampling date, the data displayed in this figure is from maximum values each day.

The inital E. coli levels measured in the beginning of period 2 are not well represented in the graph above, due to a large data variation. The results obtained from the 7th of November to the 21st of November were not impacted by heavy rainfall but still showed a clear presence of E. coli, see Figure 14.

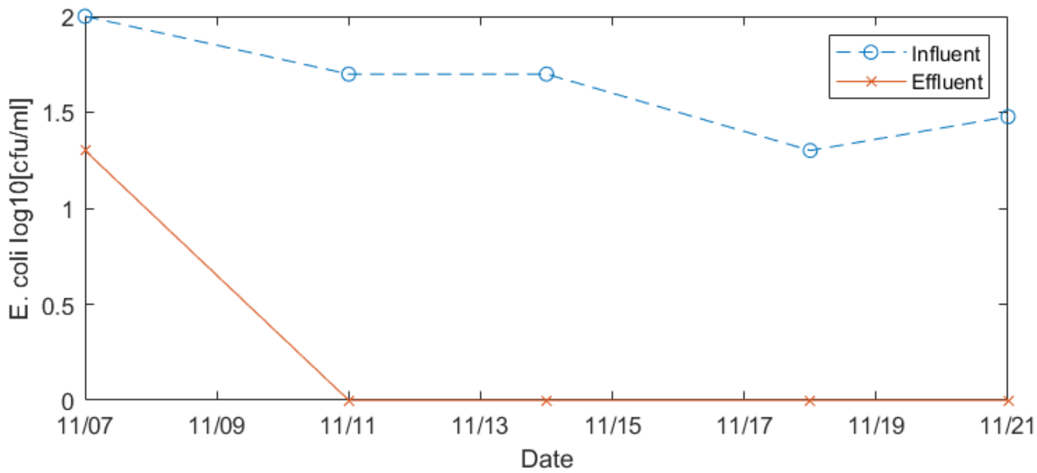

Figure 14: Concentrations of E. coli (cfu/ml) from the 7th of November to the 21st of November. Multiple plates were tested for each sampling date, the data displayed in this figure is from maximum values each day.

The filter had a consistent impact on E. coli with an average reduction of 59,3% during stable weather conditions from November 7th to November 21st, see Table 4. The majority of effluent samples obtained from the 7th of November to the 21st of November showed 0 E. coli presence in the samples, see the effluent median in Figure 15.

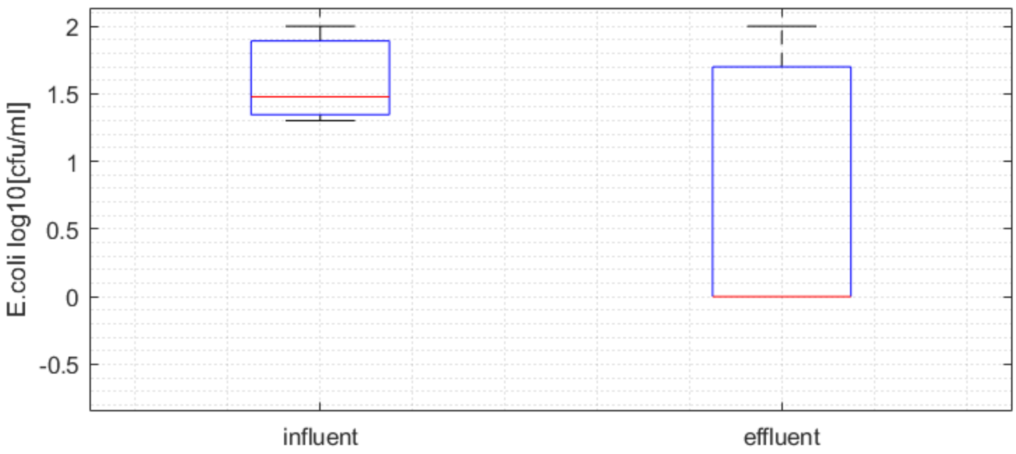

Figure 15: Concentrations of E. coli (cfu/ml) from November 7th to November 21st. The representation contains all measured data within quality range. The red line indicates the median while the blue box top limit indicates the 75th percentile and the bottom limit the 25th percentile. The whiskers represent the extreme data points that are not considered outliers. P-value: 1,53%, rejecting the null hypothesis.

All dilutions producing quality data on the 25th of November and the 2nd December displayed a large increase of E. coli. The E. coli distribution of these specific dates are displayed in Figure 16. The effluent concentrations of E. coli ranged between 1000 to 2500 cfu/ml. The effluent never reached values beneath a thousand cfu/mL on any of these dates.

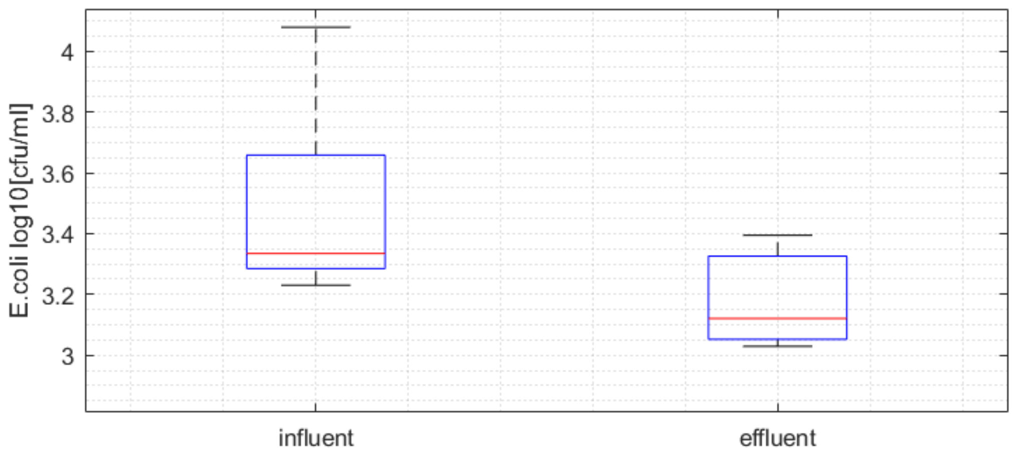

Figure 16: Concentrations of E. coli (cfu/ml) during November 25th and December 2nd. The representation contains all measured data within quality range from each date. The red line indicates the median while the blue box top limit indicates the 75th percentile and the bottom limit the 25th percentile. The whiskers represent the extreme data points that are not considered outliers. The outliers are marked with a red (+). P-value: 25%, not rejecting the null hypothesis.

Table 4: Results of mean values and average reduction % for total E.coli, and E.coli during stable weather conditions and during heavy rainfall. The reduction percentage is calculated from the mean values.

E.coli	Dates	Influent mean [cfu/ml]	Influent IQR	Effluent mean [cfu/ml]	Effluent IQR	Reduction [%]
Total	11/7-12/2	1357	1825	302,9	70	77,7
Stable weather	11/7-11/21	49	57,5	20	50	59,3
Heavy rainfall	11/25 & 12/2	4234	3542	1623,3	1057	61,7

6.2.2 Coliforms

The mean concentration of influent coliforms was 25758 cfu/ml with and IQR of 21293. The mean concentration of effluent coliforms was 7365,8 cfu/ml with an IQR of 7505. The mean reduction of coliforms in the filter was 71,4 % (0,54 log reduction). The concentration of coliform bacteria increased on the 18th and 25th of November and peaked on the 2nd of December, see Figure 17. Both December 2nd and November 25th were impacted by heavy rainfall while November 18th was not.

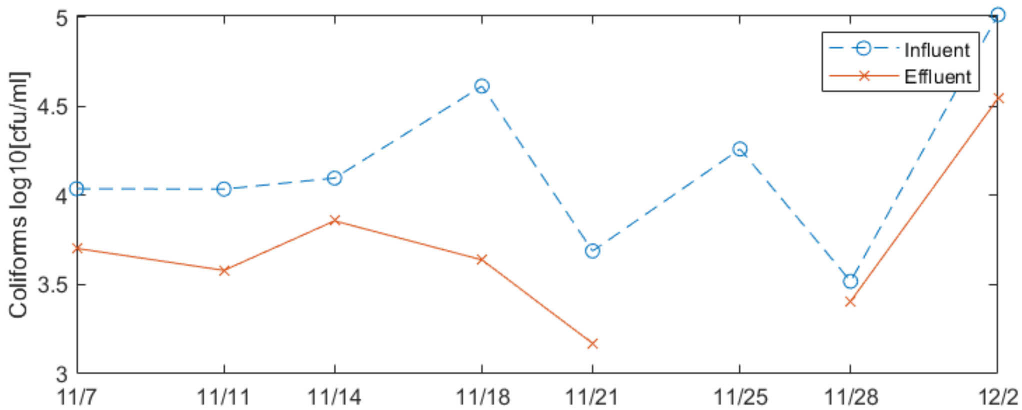

Figure 17: Concentrations of coliforms (cfu/ml) during the sampling period. Multiple plates were tested for each sampling date, the data displayed in this figure is from maximum values each day.

The quality data control for coliforms was the same as for E. coli. There needed to be between 30-300 countable colonies on all diluted samples for the data to be considered valid. The ouliers (+) in Figure 18 for both influent and effluent coliforms were from samples collected on December 2nd.

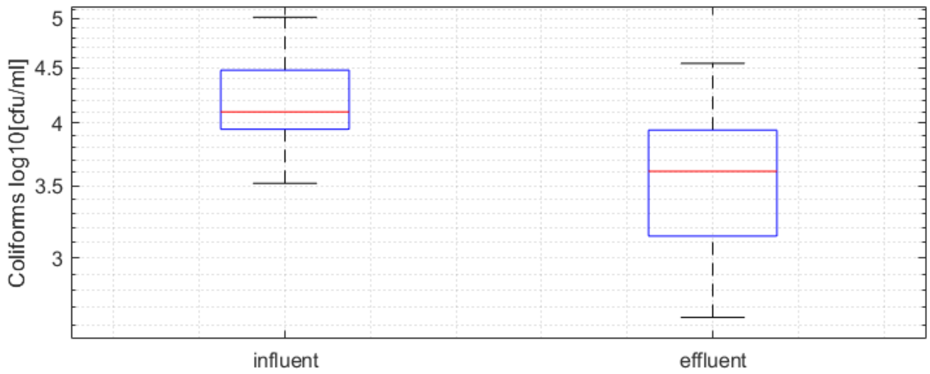

Figure 18: Concentrations of coliforms (cfu/ml) during period 2. The representation contains all measured data within quality range. The red line indicates the median while the blue box top limit indicates the 75th percentile and the bottom limit the 25th percentile. The whiskers represent the extreme data points that are not considered outliers. The outliers are marked with a red (+). P-value: 0,71%, rejecting the null hypothesis.

6.2.3 Salmonella spp.

The Salmonella spp. results showed a larger presence of Salmonella spp. in the effluent water compared to the influent water, see Figure 19.

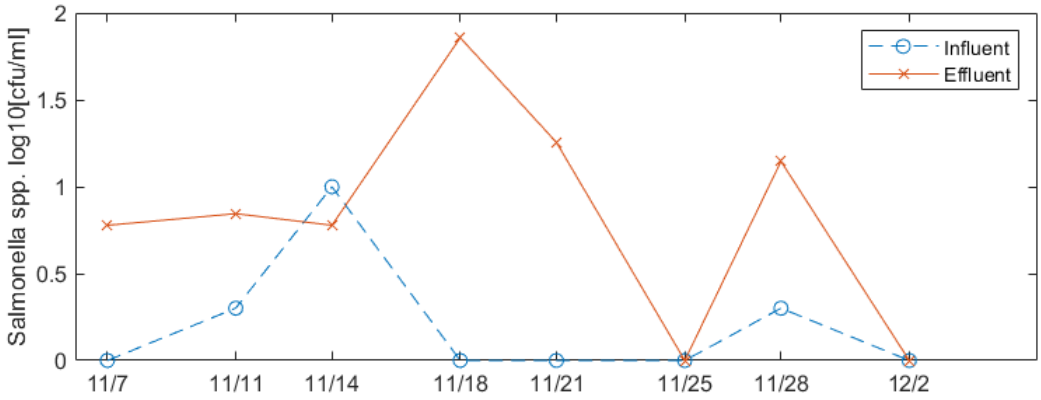

Figure 19: Concentrations of Salmonella spp. (cfu/ml) in influent and effluent water samples from each sampling date. Multiple plates were tested for each sampling date, the data displayed in this figure is from maximum values each day.

The influent water ranged between 0 to 10 cfu/ml of Salmonella spp. while the effluent normally ranged between 0 and 26 cfu/ml, resulting in an increase of Salmonella spp., see Figure 20.

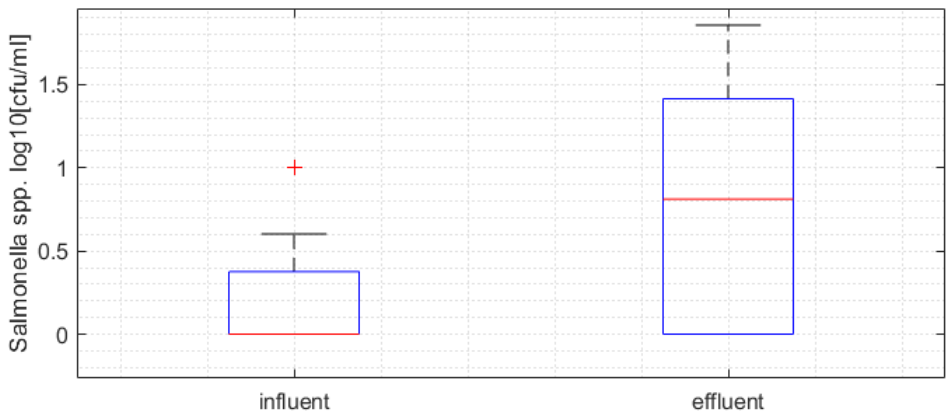

Figure 20: Concentrations of Salmonella spp. (cfu/ml) during period 2. The representation contains all measured data within quality range. The red line indicates the median while the blue box top limit indicates the 75th percentile and the bottom limit the 25th percentile. The whiskers represent the extreme data points that are not considered outliers. The outliers are marked with a red (+).

6.2.4 TSI and Urease broth test

Table 5: Results from TSI and Urease broth testing where P=Possible Salmonella spp., and +=confirmed Salmonella spp.. Tests showing negative results(-) were excluded from further testing.

Plate	Colony #	TSI Result	Urease Broth Result	Salmonella spp.
1	#1	P	P	+
	#2	P	-	
	#3	P	P	+
	#4	P	P	+
	#5	P	P	+
	#6	P	P	+
	#7	P	P	+
2	#1	P	-	
	#2	-		
	#3	P	P	+
	#4	P	P	+
	#5	P	-	
3	#1	-		
	#2	-		
	#3	-		
4	#1	P	P	+
	#2	-		
	#3	P	P	+
5	#1	P	P	+
	#2	P	-	
Total	20	75% P	55% P	55% +

The TSI and Urease tests showed that 55% of the growths were indeed Salmonella spp.. These results are from five different XLD plates which contained samples from two different dates. Hence, this result only shows an estimation of the Salmonella spp./proteus rate of growths on the XLD plates.

6.2.5 Total Solids

The vertical garden had an average TS removal of 26,6%. The distribution of TS in the influent and effluent water samples were quite similar, see Figure 21. For mean values and average removal values for TS, VS, and FS, see Table 6, Section 9. The quality data range was set at 2,5-200 mg/L TS after evaporation. Sample volumes that yielded more or less residue was not considered to produce valid data.

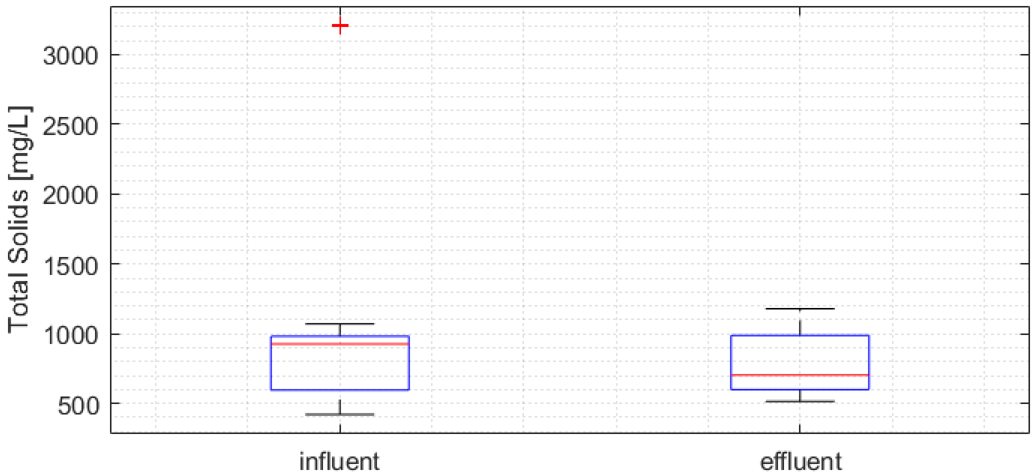

Figure 21: Total Solids during period 2. The representation contains all measured data within quality range. The red line indicates the median while the blue box top limit indicates the 75th percentile and the bottom limit the 25th percentile. The whiskers represent the extreme data points that are not considered outliers. The outliers are marked with a red (+). P-value: 95%, not rejecting the null hypothesis.

The VS tests showed that approximately 21,4% of the influent solids and 22,7% of the effluent solids were organic matter, calculated from mean values. The volatile solids were reduced by 22,2% in the filter. See Figure 28 and 29 in Appendix B for concentrations of VS and FS or see Table 6 for mean concentrations. The charcoal residue in the effluent samples, see Figure 22, were present after ignition.

There was a 27,8% average reduction of FS, see Table 6, implying that approximately 27,8% inorganic matter was removed when the water passed through the filter. The visual difference between the influent and effluent water showed that charcoal particles were numerous in the effluent water, see Figure 22. The charcoal particles are from the charcoal inside the vertical garden and were present in the effluent samples throughout period 2.

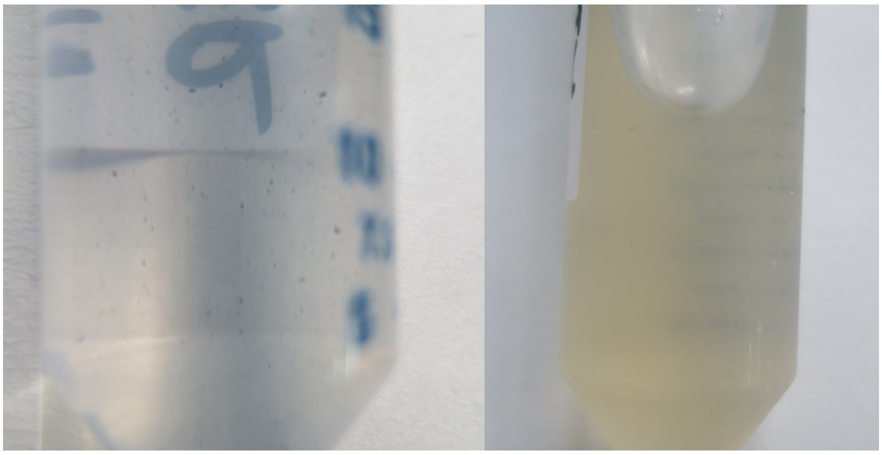

Figure 22: Visual difference between effluent water (left) and influent water (right). The presence of charcoal is visible in the effluent water samples.

Table 6: Results of mean values and average reduction % for total solids, volatile solids, and fixed solids. The reduction percentage is calculated from the mean values.

Solids	Influent mean [mg/L]	SD	Effluent mean [mg/L]	SD	Reduction [%]
Total solids	1060,6	223,8	778,4	223,5	26,6
Volatile solids	227	139	176,6	93,5	22,2
Fixed solids	833,6	727,3	601,8	204,5	27,8

6.2.6 Biochemical Oxygen Demand

The average reduction of BOD was 58%, showing an estimation of the overall effect of the vertical garden. The relationship between influent and effluent BOD varied throughout the period but there was a constant reduction of BOD in the effluent sample. The inluent BOD had a maximum of 14,76 mg/L and minimum 3,61 mg/L DO depletion. The effluent BOD had a maximum of 5,03 mg/L and minimum 2,02 mg/L, see Figure 23. The peaks were not from the same sample date.

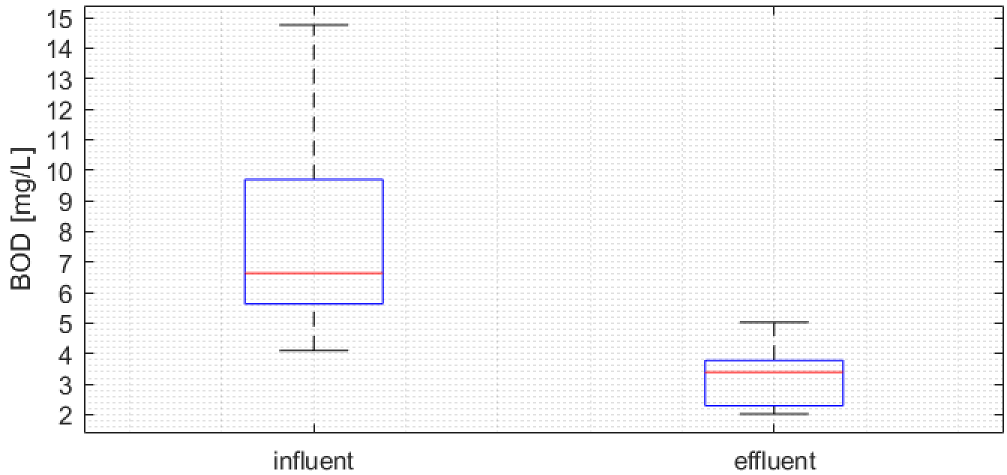

Figure 23: BOD measured during period 2. The representation contains all measured data within quality range. The red line indicates the median while the blue box top limit indicates the 75th percentile and the bottom limit the 25th percentile. The whiskers represent the extreme data points that are not considered outliers. The outliers are marked with a red (+).

The quality data range for distilled water was set at DO>7,5 mg/L and DO depletion less than 0,2 mg/L. The distilled water used had DO levels below 7,5 mg/L. Since dilutions were needed at certain times for the data to fall within the DO-meters valid data range, the quality data range DO>7,5 mg/L for distilled water was discarded.

6.2.7 Chemical Oxygen Demand

The COD had an average 19,7% reduction when passing trough the vertical garden. The influent COD varied more than the effluent COD, see Figure 24. For mean influent and effluent COD levels, see Table 7. .

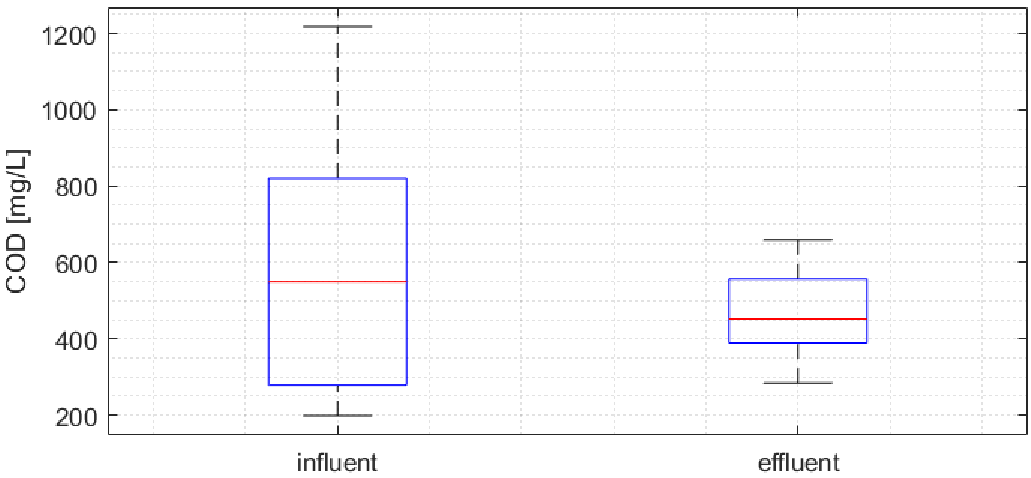

Figure 24: COD measured during period 3. The representation contains all measured data within quality range. The red line indicates the median while the blue box top limit indicates the 75th percentile and the bottom limit the 25th percentile. The whiskers represent the extreme data points that are not considered outliers. The outliers are marked with a red (+). P-value: 0,87%, rejecting the null hypothesis.

There was a significant nitrogen uptake in the filter in comparison to the phosphor uptake, see Table 7. For data distributions and median values for Tot-P and Tot-N see Appendix B.

Table 7: Results of mean values and average reduction % of COD, Tot-N, and Tot-P. The reduction percentage is calculated from the mean values. (n)= Number of observations.

Parameter	(n)	Influent mean [mg/L]	SD	Effluent mean [mg/L]	SD	Reduction [%]
COD	7	590,9	363,8	474	126,8	19,8
Tot-N	7	20	12,8	4,7	2,2	76,5
Tot-P	7	1,07	0,52	0,95	0,11	11,5

6.3 Functionality of the vertical garden

The conducted tracer test indicated that the filter has a mean residence time of 17 hours and 40 minutes, when introduced to a HLR of 120 L/m2/day. That is, 50 percent of the tracer pulse was retrieved 18 hours after injection. The graph below shows the accumulated time passed since the pulse injection on the x-axis. The measurements were collected during 2 days, due to respect of campus opening hours, this is represented by the time discontinuity of the plotted graph on the X-axis. The Y-axis is a relative representation of the conductivity accumulated with volume over time, in relation to the conductivity and volume the injected initial pulse.

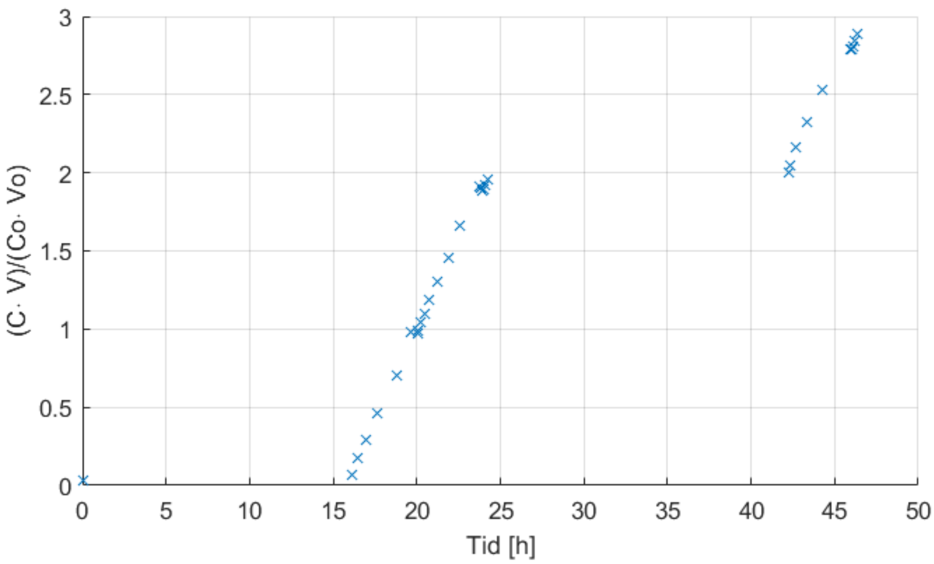

Figure 25: Tracer residence time

Most of the designed attributed of the vertical garden functioned well during the sample period. No clogging or accumulation of water in the bottom basin was recorded. The top part of the garden was kept intact throughout the project and spinach seedlings evolved over time, see Figure 26.

Figure 26: VG first implemented in Kibera, being watered by Patrick (left), VG right after seedlings have been planted (middle) and VG at the end of the sample period (right). Authors picture

The seedlings planted in the garden during week 1 were measured at a mean height of 15 cm, exclusive of the root. At the time of harvest the spinach had grown on all rows of the garden. The three main zones (lower, middle and upper) generated mean lengths of 21,6 22,3 and 24,9 from 6 random sampled leafs of each section. This generated an average size of 22,9 cm. This results in a 153% growth compared to length size in beginning.

Figure 27: Picture taken of Spinach seedlings (left) and final spinach yield after 5 weeks (right). Authors figure.

The microbiological analyses carried out on total 9 spinach leafs (3 leafs from each lower, middle and upper row) showed that the samples contained 0 CFU/ml of either E. coli, Salmonella spp. or coliforms.

6.4 Effluent quality for irrigation

The results dfrom the effluent water quality showed a reduction of most parameters in comparison to the influent. However, the E. coli still varies a lot depending on weather conditions which has been marked out in Table 8.

Table 8: Results from effluent water samples showcasing the quality and characteristics of the water after filtertration in the vertical garden. *=Maximum and minimum values from samples after heavy rainfall. Mean values are calculated from the total data with no regard to weather conditions. The guideline values are taken from Table 1 and 2, for references and further guideline values see each Table. Degree of restriction of use is set from the total mean value of the specified parameter. [1]=Degree of restriction of use varies depending on weather conditions. (n)= Number of observations.

	E. coli [cfu/ml]	Coliforms [cfu/ml]	Salmonella spp. [cfu/ml]	TS [mg/L]	pH	EC [μS/cm]	Tot-N [mg/L]	Tot-P [mg/L]	COD [mg/L]	BOD_5 [mg/L]
Mean	302,9	7365,8	14,2	778,4	8,2	1396,4	4,7	0,95	474	3,32
Maximum	2480*	$35{\cdot}10^3$*	72	1180	8,5	1645	9	1,08	660	5,03
Minimum	0	440	0	515	7,68*	829	2,5	0,76	284	2,02
(n)	17	12	18	11	8	8	7	7	7	6
Quality Guideline	$\leq$1000 see Table 1	-	-	<450 see Table 2	6,5-8,4 see Table 2	<700 see Table 2	<5 see Table 2	-	-	-
Degree of restriction on use	Suitable[1]			Slight to moderate	None	Slight to moderate	None			

7 Discussion

7.1 Current irrigation water from the Nairobi dam

A few key characteristics of the current irrigation water were noticed during the sampling period. The major key characteristic is the variation of water quality in the Nairobi dam depending on runoff levels from Kibera. Out off all the parameters measured, E. coli is the one most influenced by weather and runoff. The fecal contamination increased significantly on November 25th and December 2nd due to the increased runoff from Kibera during the heavy rains, see Table 4. There was an evident difference at the sample collection point when runoff increased, the water was darker and looked and smelled like pure wastewater. Fecal contamination indicates the presence of pathogens and poses as a health risk for consumers and the farmers handling the water (Hesphanhol and Prost, 1994). Even though the Salmonella spp. results show a larger amount of Salmonella spp. in the effluent than the influent, the Salmonella spp. most likely origins from the influent water. Salmonella spp. presence was not consistent in the irrigation water and usually varied from none to low quantities. Since samples were only collected two times a week it is hard to give an overall image of the Salmonella spp. contamination in the Nairobi dam. Either way, small quantities of Salmonella spp. still pose as a further health risk for consumers and farmers. Salmonella spp. can origin from the feces of the animals living in Kibera, such as dogs, pigs and goats. This also resonates with the smaller quantities of Salmonella spp. versus E. coli which might be because heavy rainfall has a smaller impact on Salmonella spp. since not all animal feces end up in the wastewater drenches.

The solids present in the irrigation water is in the moderate to severe degree of restriction on use, see Table 2. However, solids impact irrigation systems such as drip irrigation which is not currently being used at the Nairobi dam and therefore pose as a smaller threat.

The salinity of the water may impact crop root systems in a way that decreases yield or crop health. Especially when the water table is close to the root zone which can be assumed to bee the situation with the fields close to the Nairobi dam wetlands. If the salinity (EC) measured in the irrigation water is the same as the water table, the salinity will eventually form in the root zone. Therefore, the salinity poses as one of the more hazardous parameters measured in the irrigation water.

7.2 How effective is the local charcoal as a treatment filter, during the initital stage of its lifespan?

7.2.1 Pathogen removal

The main form of bacteria reduction process is done through filtering, sorption or biofilm degradation. It is hard to be certain which of the three processes accounts for the greatest removal of pathogens. But, previous literature indicates a longer required time for a biofilm development than what was provided by the sampling period. Therefore, it is most likely that it is the filtration and sorption properties of the filter that have yielded the overall removal results. Processes like filtration and sorption efficiency declines over time, as adsorption surfaces and pores get occupied. Instead, the process of biofilm degradation can have an important role in pathogen removal as time goes. This project did not have enough time to be able to analyse the filters biofilm possibilities. Therefore, this report can not answer how the filter might work in the future, with regards to removal efficiency. However, the collected data and microbiology analyses provides an overview of the filter removal efficiency of the present state of the filter. That is, a start-level state with a lack of biofilm development and with full availability of adsorption surfaces and pore attachment.

Counting coliform bacteria was a method used to retrieve an overview of the overall microbial reduction. Since coliforms were always present in the samples, regardless of the contamination state of the influent water. The collected samples showed that the filter yielded a 71,4 % (0,54 log) mean reduction of coliforms. For E.coli analyses, a slightly larger mean reduction level of, 77 % (0,65 log), was found, se Table 4. The faecal bacteria is a known indicator for other pathogens, and there is a clear advantage of knowing its reduction rate. The results link the level of E.coli contamination in the samples directly to the amount of run-off. Heavy rainfalls lead to a greater run-off from Kibera down to the Nairobi dam, bringing a greater amount of waste with the drainage. This variation in contamination posed a challenge in the lab when choosing a dilution, but does give a representation of contamination distribution which reflects reality for Kibera. These weather changes are common to Nairobi, especially during rainy season. Data collected during during the 25th of November and the 2 December indicate that the filter can perform well during heavy rainfall, providing a 61,7 % (0,41 log) mean removal percentage of E.coli, see Table 4.

Regardless of the Salmonella spp. contamination level, it was expected that effluent samples would show equally high or lower levels of Salmonella spp. than influent samples. However, Salmonella spp. analyses during the trial period showed results that differed from this hypothesis. The filter does not seem to have any sanitary effect on Salmonella spp.. Instead, there are indications that Salmonella spp. can linger in the filter, once it has been introduced through irrigation. This theory is based on Figure 19, which shows the Salmonella spp. analyses in accordance to the sample collection time. The 18th of November represents the highest value of Salmonella spp. analysed from the outflow from the charcoal garden. From this date until the 2nd of December Salmonella spp. is showing up in the outflow. The virus seems to slowly decrease over time, gradually getting flushed out of the garden.

Comparing these results to prior studies performed on biochar as a removal media of water contamination, presented in literature review. The removal performance of pathogens found in the charcoal vertical garden is generally lower. According to Fernando Perez Mercados studie in 2019, the 'normal' bacteria and virus removal rate of biochar is somewhere between 1 and 4log10 for virus and 2log units for bacteria. However, this study was conducted with biochar of homogenus sizes between 1,4 and 5 mm in diameter, exposed to a constant HLR from a water source with a specific contamination level and organic matter. In other words, the study was not a vertical garden exposed to a water source of fluctuating quality. Specific data of bacteria or virus removal from a construction such as a vertical garden has not been studied in such terms before.

Sometimes it was hard to distinguish proteus growths from Salmonella spp. growths on the XLD plates. To be certain that the growths counted as Salmonella spp. was in fact Salmonella spp. and not proteus a random testing of colonies from five plates with different collection times were analysed with TSI and Urea testing. From these testing's, around 55 % of all coliforms analysed turned out to be Salmonella spp., see Table 5. This does not represent the reality for all plates, but since the TSI and Urea testing was too time consuming to apply to every Salmonella spp. analyse, the percentage should be used as a rough estimate of the Salmonella spp. and proteus fraction of growths on the XLD plates.

Previous studies at the university of Nairobi had also concluded that the Salmonella spp. was not a common occurrence of Kibera. As such, it was important to conclude that the bacteria found in effluent samples did not originate from another source. As a result, the soil used for the plants was analysed for Salmonella spp.. Resulting soil analyses showed that no Salmonella spp. was present in the soil. Therefore, it was decided that the Salmonella spp. found in the filter, most likely, originated from the irrigation water.

With regards to the amount of Salmonella spp. found in the influent samples, it was surprising that such low traces of Salmonella spp. were continuously found in the water source throughout the sample period. There are no definite answers as to why this was, but three main ideas were discussed. Firstly, it is conceivable that the virus spreads more like a pulse in the runoff, perhaps originating from an animal being slaughtered during the weekend. In such a case, it is possible that the twice weekly sample collection simply missed the peak of the 'Salmonella spp. pulse'. It is also possible that the Salmonella spp. amount in the influent water was too diluted to show up on the XLD plates, and that the effluent water simply gave a more concentrated sample collection of Salmonella spp.. The final thought is that the low amount of Salmonella spp. found in influent samples was an accurate representation of reality. If such was the case, it means that the smaller doses of Salmonella spp. which was introduced to the garden got stuck in the filter and grew in numbers until it was flushed out, four days later, see Figure 19.

7.2.2 TS, VS, BOD5 and COD

The BOD results work as an estimation of the filters capabilities. The effluent BOD was reduced in comparison to the influent. This shows that there is a generally small reduction of organisms and chemicals that can consume oxygen, indicating the filters treatment efficiency. However, the BOD measurements were subjugated to certain "errors". To produce a quality BOD assessment, certain chemicals, minerals and nutrients need to be added to the samples or the distilled water before measurement. These chemicals were not available for this study and therefore pose as a clear source of error. The quality of the distilled water used for the diluted samples were also a point of interest since it was not consistent and usually had a lower initial DO value than optimal (7,5 mg/L). The overall values of both influent and effluent samples were lower than expected which led to the majority of the samples being undiluted. This reduces the nutrient and chemical error previously mentioned due to the natural nutrients and minerals available in the influent and effluent samples. The low BOD values and the overall low DO reduction combined with the high proportions of FS indicates a potential presence of heavy metals in the samples. If heavy metals are present, they have a toxic effect on the organisms. If the samples become toxic from heavy metals, the majority of organisms in the sample will probably die off which impacts the DO reduction. Without a healthy foundation of organisms, the BOD results are no longer representable.

The COD results are not influenced by heavy metals or other toxic matter since the COD process only measures the chemically degradable oxygen in the sample. However, COD values and BOD values usually have linear relationship with COD being the larger value. The BOD/COD ratio for untreated wastewater usually ranges between 0,3-0,8 (TUHH, 2019). The BOD/COD ratios from the influent effluent samples were lower than 0,014 which also indicates a toxic environment in the BOD samples. Therefore, it is most likely that the BOD results are not representing the actual values of the influent and effluent water. However, some credibility should be considered for the difference of influent and effluent BOD since both samples are subjugated to the same errors and the same possible toxic environment. Which means that the BOD results, regardless of its errors, show that the filter is having a reducing impact on BOD.

The vertical garden removed 26,6% of the total solids but it is hard to estimate the impact of the charcoal particles present in the effluent samples. It is also hard to reason the extreme value noticable in Figure 21. Since we don't know for sure what gave reason for this high value of TS, we cannot discard the result since there might be some other natural reoccurring explanation behind it. The reduction was not enough for the effluent water to be without a degree of restriction of use, see Table 8. The ratio of VS and FS remained quite similar for the influent and effluent samples, showing an overall reduction of solids not emphasized on either organic or inorganic matter. A smaller grain size of charcoal might have increased the vertical gardens filtering capability in removing solids, yielding in effluent water which would be safer to use for irrigation systems. However, since there is no irrigation system sensitive to solids currently used in Kibera i.e. drip irrigation, this parameter is less significant as of this moment. Should there come a time when i.e. drip irrigation systems are placed in the fields, the solids in the water pose a greater risk.

The effluent samples continuously carried charcoal residue, see Figure 22. The charcoal residue was visually more prominent in the initial effluent water and decreased for every second until visibly clear. This was of course expected in the beginning when you fill a sack full of crushed charcoal, but it was expected to decrease over time. However, there was less charcoal residue in the effluent water after the vertical garden was flushed before being installed in Kibera. It is hard to estimate if the charcoal residue slowly decreased during the sampling period since it was only noted visually. It is also hard to estimate what proportion of the effluent solids were charcoal residue since the majority of the solids are not as visually representable as charcoal.

7.3 How functioning is this design of a vertical garden?

Even though spinach grew quite evenly across the garden it did not yield as big of a crop as expected. The crop had increased by 153% in size compared to the initial mean length of the seedlings planted in the beginning, see Figure 27. However, this is based on lenght measurements. Comparing spinach weights would have given further constructive information of spinach yield, but was not possible when planning the seedling planting. According to Mmoja (2019) the spinach plant should have grown at least on third more in length and would have reach its full should size within 4 weeks, if planted in an ordinary horizontal garden during optimum soil and irrigation conditions. The lower yield in spinach than expected might have been because by the number of seedlings planted in the filter. The vertical garden was covered with 25 plants and even though it is believed that all seedlings got enough water, they might not have had space enough to grow. This could either be due to the load of crop or to the size of the soil-cups they were confined in. The half-litre bottles were punctured with holes which would allow for smaller roots to spread but in the long run it might restrain the crops' ability to grow into its full size. It is also believed that the spinach was positively effected by the amount of nutrients retained from the wastewater. Particularly by nitrogen, as data showed that out of 20 mg/L Tot-N received from the influent water, in general, only 4,6 mg/L made its way out of the filter, see table 7. In other words, the filter retained a mean value of 15,3 mg/L Tot-N, some of which can be utilized by the spinach crops.

With regards to the lab results of the spinach microbial sampling, we can assume that the top part of the garden acts as a protective shield against water splashing from the influent water, see Figure 26. This because neither Salmonella spp., coliforms or E.coli were present on any of the spinach. However, it should be mentioned that the spinach is not sheltered from the precipitation. This means that the spinach could have been rinsed off contaminations through heavy rainfall, prior to the crop harvest. In other words, the lab results can not guarantee that the ¨top protection¨ of the garden works according to the design.

Choosing an appropriate charcoal grain size depends on the quality of the incoming water. During this period of testing, the main size 1,7 mm-4 mm was small enough to give a good bacteria reduction with an 18-hour retention time in the filter, see figure 25 and still be big enough to avoid clogging of the system. Since the pathogen removal during testing was mainly due to filtration and sorption qualities, the designed grain size gave a good enough retention time. However, if the filter were to create a biofilm layer in the future, the grain size might no longer be small enough to generate an appropriate retention time. Since there is a higher chance of biofilm degradation of pathogens when longer contact time is provided.

Previous studies of prototypes of biochar filters in the same grain size range, 1,4 to 5 mm, has shown much greater mean retention times of 66 to 85 hours, than what was produced for the charcoal vertical garden (Perez-Mercado et al., 2019). However, these studies were conducted on smaller homogeneous biochar filters that were continuously introduced to an influent pumping rate of water. Whereas the tracer test conducted on the vertical garden during period 1 represented the water regime that would be conducted during the sampling in period 2. That is, the filter was loaded with water three times a day during tracer analyses. Also, the effluent water analysed during tracer testing could only be collected during day-time (office-hours) and the additional water emitting from the garden during night time was not accounted for. Furthermore, a tracer test is usually performed with sodium chloride as this substance does not interact with the filter medium. In our case, standard table salt was used to create the injection pulse. This salt was later discovered to contain additional minerals which could have interacted differently with the filter. These error combined, could give a further explanation to why the breakthrough curve 25 shows a higher value than 1 on the Y-axis. When actually, the graph should give the relative representation of the conductivity that had been accumulated over time (finally reaching 1 when the entire pulse has passed through the system).

There were a few issues when procuring the chosen charcoal grain size. As explained in Section 5.2, three different techniques were used when crushing charcoal. Technique 1 and 2 produced a greater quality of grain sizes compared to technique 3, but their processes were too time-consuming, and the techniques fell short under design restriction 1, making the garden difficult to construct. Technique 3 produced a bigger quantity of appropriate charcoal sizes, per time unit, than 1 and 2. However, the technique also crushed the charcoal into too small pieces and parts of the charcoal was lost. This could have a financial effect on constructing the garden, as the biochar is the most expensive part of the design but is considered favourable compared to the time-consuming processes 1 and 2. Nonetheless, the garden is still easy to build if using technique 3, it is simply a lot of hard work. Since much of the materials used for building the garden had been re-used the biggest economical strain on the design was buying the charcoal itself. When it is actually the smaller charcoal residues left in the bottom of the bag, or piled on the floor of the vendor that is of interest. Maybe, if there was a demand for charcoal gardens in Kibera a business opportunity in selling charcoal residue might develop. This could lower the price of buying charcoal as well as making it less time consuming to constructing the garden.

Another concern with the garden design regards the bottom basin that the filter was placed in. Foremost regarding the wooden-parts installed in the bottom of the basin, but also the inside surface of the plastic bottom. Throughout the sampling period it was noticed that the inside, even though it was drained, was always a little damp and algae growth was noticed around the tap in the bottom edge of the basin. This environment of damp and warm places has a risk of creating unwanted bacterial growth which could affect the effluent water quality. Also, the design of the soil-cups was based on idea that soil and cups are accessible, free and easy to collect. Which is partly true, however, precautions should be made when choosing a site for soil collection and when picking appropriate cups. It is not advised to collect planting soil directly from contaminated parts of the Kibera slum or to collect and use cups that have not been cleaned, as this can have a negative influence on the filter performance.

7.4 Is the quality of effluent water, collected during the first stage of the filter lifespan, appropriate to be reused as irrigation water?

As shown in Section 6.2, the vertical garden has a reducing affect on the majority of parameters except for Salmonella spp.. The more substantial reductions are on E. coli and coliforms. Despite these reductions, during rainfall and floods the effluent water is still governed by the same degrees of restrictions as the influent, see Table 8. The major cause for this is the variation in influent water quality, with radical changes in fecal contamination depending on the weather conditions, see Figure 13.

The influent concentrations of E. coli measured during the sample period are either lower than the restriction value or high enough for the reduction not to be enough to bring it below the restriction value, see Figure 15 and 16. However, the reduction still indicates a removal of pathogens. It could be well argued that the treated effluent carries a smaller fraction of fecal pathogens compared to the influent. Further data on year-round values of E. coli concentrations in the Nairobi dam would help estimate the benefits of this type of filter since there might be periods of other E. coli concentrations. The BOD and COD reduction also implies that the filter is having an overall positive affect on the water quality.

The effluent water also contains levels of solids that may have a negative effect on irrigation systems, should there be any. These result were very interesting due to the effluent water containing charcoal particles throughout the sampling period, as shown in Figure 22. This argues that the local charcoal might not be ideal as a filter medium. However, the sampling period only stretched for five weeks and it is hard to estimate how the charcoal residue would behave in the future.

There was also a clear uptake of nitrogen in the filter, see Table 7. This uptake may have have been utilized as a fertilizer by the spinach, resulting in the 153 % average spinach growth. The Phosphorus occurred in lesser concentrations than nitrogen and did not reduce significantly in the filter or by crops. However, the removal rates of the minerals are expected to decrease if the vertical garden would continue to be used, as the sorption efficency of the filter would decline over time.

The results show that the effluent water is still not high-quality irrigation water, but it is more suitable for use than the influent water. The EC concentrations still pose as a risk to crops and the fecal contamination during heavy rainfalls is still a health risk for consumers and farmers. However, due to the reduction of these parameters, the risk should be lower.

8 Conclusion and future recommendations

This research aimed to evaluate the sanitary affect a charcoal vertical garden can have on drain-water collected from the Nairobi dam in Kibera. The objective was also to analyse whether or not the effluent water quality generated from the filter was of good enough to be re-used as irrigation water for the local crops.

Based on microbiology and water chemistry analyses it can be concluded that the charcoal filter had a 60-70 % removal efficiency of E.coli and coliform removal and a zero removal percentage of Salmonella spp.. The research results also illustrates that the filter reduced TS, VS, FS and COD from the influent water source by 26,6, 22,2, 27,8 and 19,8%. Furthermore, the filter had a 76,5 and 11,5% uptake of the plant nutriens tot-N and tot-P. Based on these results it becomes clear that the filter indeed has a sanitary impact on the water source, but that it still falls short on the required EC levels, E. coli amount and Salmonella spp. count specified for the irrigation water quality guidelines set by FAO, (Ayers and Westcot, 1994). This becomes especially true during periods affected by heavy run-off, as this has been proven to have a direct impact on the influent water quality.

By constructing a filter from local charcoal and low-priced materials, this thesis has shown that small investments can make a big difference in sanitation development. The results indicate that spinach is a suitable crop to grow in a vertical garden and that a ´splash protection´ could be an appropriate design investment. The overall design of the filter resulted in an easy built, climate positive vertical garden that produced a good percentage of removal without indications of system clogging.

While results of a higher count of Salmonella spp. in effluent water samples compared to influent samples limits the generalizability of the result, it provides new insight to how a charcoal filter would interact with some viruses, in the beginning of its lifespan. The COD results measured in period 3 also indicates that the BOD results are impacted by something with a toxic presence.

Referring to the literature review and the research that has already been conducted on vertical gardens and biochar filters, this thesis has provided some important insight. First of all, it has been proven that a vertical garden can provide a good crop yield result when filled with charcoal and cups of soil, instead of 100% plant soil. Furthermore, this research has been focused on the function of local charcoal compared to previous studies conducted on biochar that has been specifically produced to be used in treatment solutions and/or filters. In this way, the thesis has combined two already researched topics of vertical gardens and biochar to a new research track of ´charcoal vertical gardens´. The findings of the thesis confirm the theory that considerable microbial removal can be achieved for biochar filters and shows that this theory also can be applied to the local charcoal produced in Kibera. The thesis findings also challenge the idea of vertical gardens being vulnerable to clogging, when used as sand filters, and that the resulting vertical garden crops produced are very un-evenly sized with much bigger yield in the top of the garden.

To better understand the implications of the these results, it is suggested that future studies includes analyses of heavy metal contaminations in influent samples and analyses of possible heavy metal reduction in the filter. Further data collection is needed, within an extended sample time period, to determine the relationship between charcoal filter and possible biofilm development and degradation. It would also be of interest to further analyse the charcoal properties itself, to example, determine the charcoal specific surface area in comparison to that of certain types of other biochar.

Returning to the problem statement, this research has provided an economical, easy-to-build, space-saving solution to improve the Kibera drain-water quality whilst providing the user with an extra source of food-income. Even though the filter falls short in some terms of producing water with good enough quality to re-use as irrigation for the local farmers, it is still reducing enough pathogens to be considered worth the investment.

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9 Personal communications

Mmoja, Patrick Ule (2019), Kibera resident, Continous interviews during November and December 2019.

Appendix A

Pathogen measuring

Measuring E. coli

E. coli can be measured using the plate-count method with a specific medium also known as agar. There are different kinds of agar depending on what bacterium one is measuring. The agar contains a mix of substrates that makes sure that the bacteria in focus thrives and reacts in a way that it will be distinguishable while unwanted bacteria gets inhibited. The agar is placed in clear circular petri plates and the sample is spread on top of the agar. The plate is then placed in an incubator at temperatures that are hospitable for the bacteria in focus. In E. coli's case, the agar contains the substrate combination X-glucuronide by ß-D-glucuronidase and Salmon-GAL by ß-D-galactosidase. E. coli is able to cleave both these substrates which other coliforms cannot. The cleavage of these substrates results in dark blue to violet colonies which are distinguishable from the salmon red coliform colonies. The agar also contains an inhibitor for gram-positive bacteria (Millipore, 2019).

Measuring coliforms

Agar used for E. coli measurements, such as Chromocult agar, can be used for coliforms as well. The principle is the same but coliforms are generally only able to cleave the Salmon-GAL by ß-D-galactosidase resulting in salmon red colonies in difference to the dark blue E. coli colonies. Coliforms thrive in the same temperatures as E.coli and the tests can be executed simultaneously (ibid.).

Measuring Salmonella spp.

Salmonella spp. can also be measured using the plate-count method. One of the more common agars for Salmonella spp. measurements is the Xylose Lysine deoxycholate (XLD) agar. The agar consists of three types of sugar: xylose, lactose and sucrose. The agar is red but changes color due to pH change when fermentation takes place. This distinguishes Salmonella spp. and Shigella due to the fact that Shigella can't ferment xylose resulting in no color change. Lysine is included to help separate Salmonella spp. from other non-pathogens. Salmonella spp. also has the ability to consume thiosulfate which results in colonies with black centers to visibly isolate them from the Shigella colonies. Other gram-negative lactose-fermenting bacteria such as E. coli would also result in a change in pH to turn the agar yellow, but it would not consume thiosulfate resulting in clear colonies with yellow surroundings (Aryal, 2019).

Appendix B

Data distributions for VS, FS, Tot-N, and Tot-P

Volatile Solids

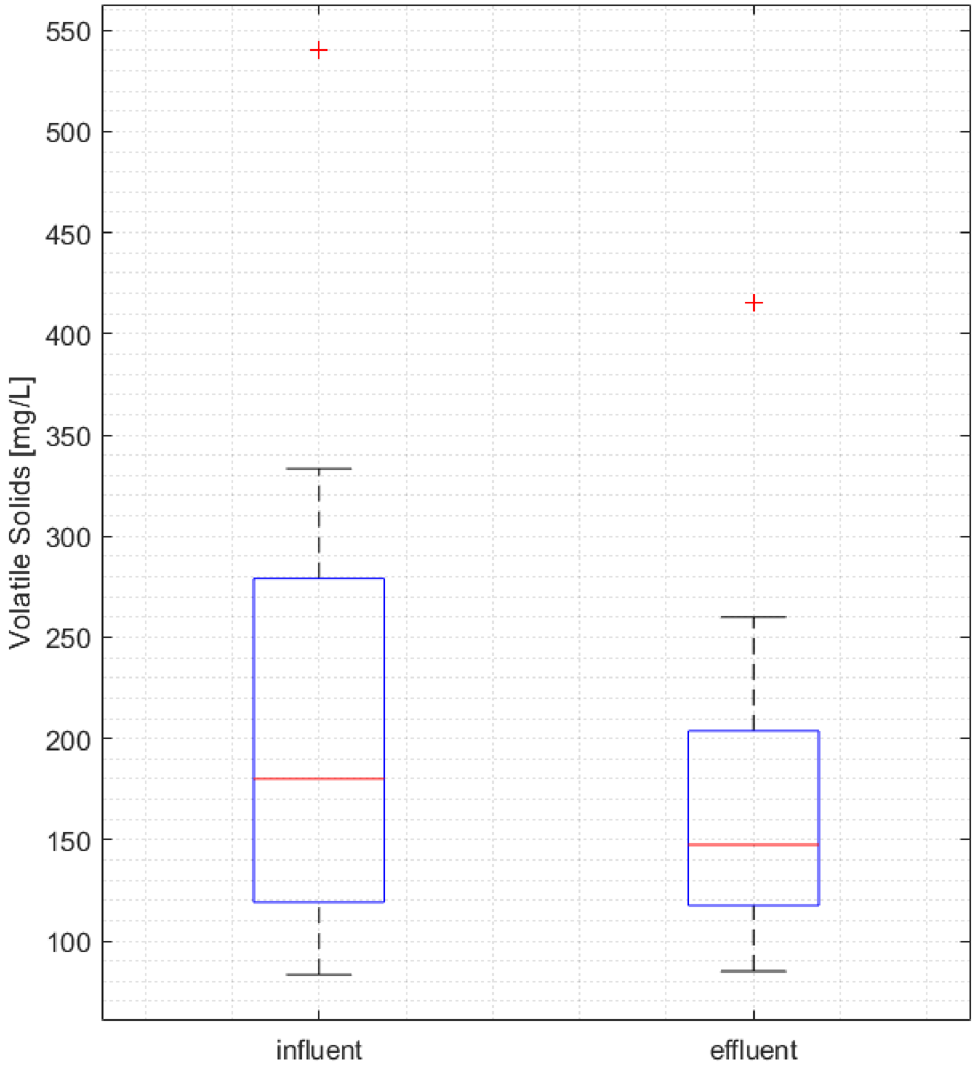

Figure 28: Graphical representation of the occurrence of volatile solids during period 2. The red line indicates the median while the blue box top limit indicates the 75th percentile and the bottom limit the 25th percentile. The whiskers represent the extreme data points that are not considered outliers. The outliers are marked with a red (+).

Fixed Solids

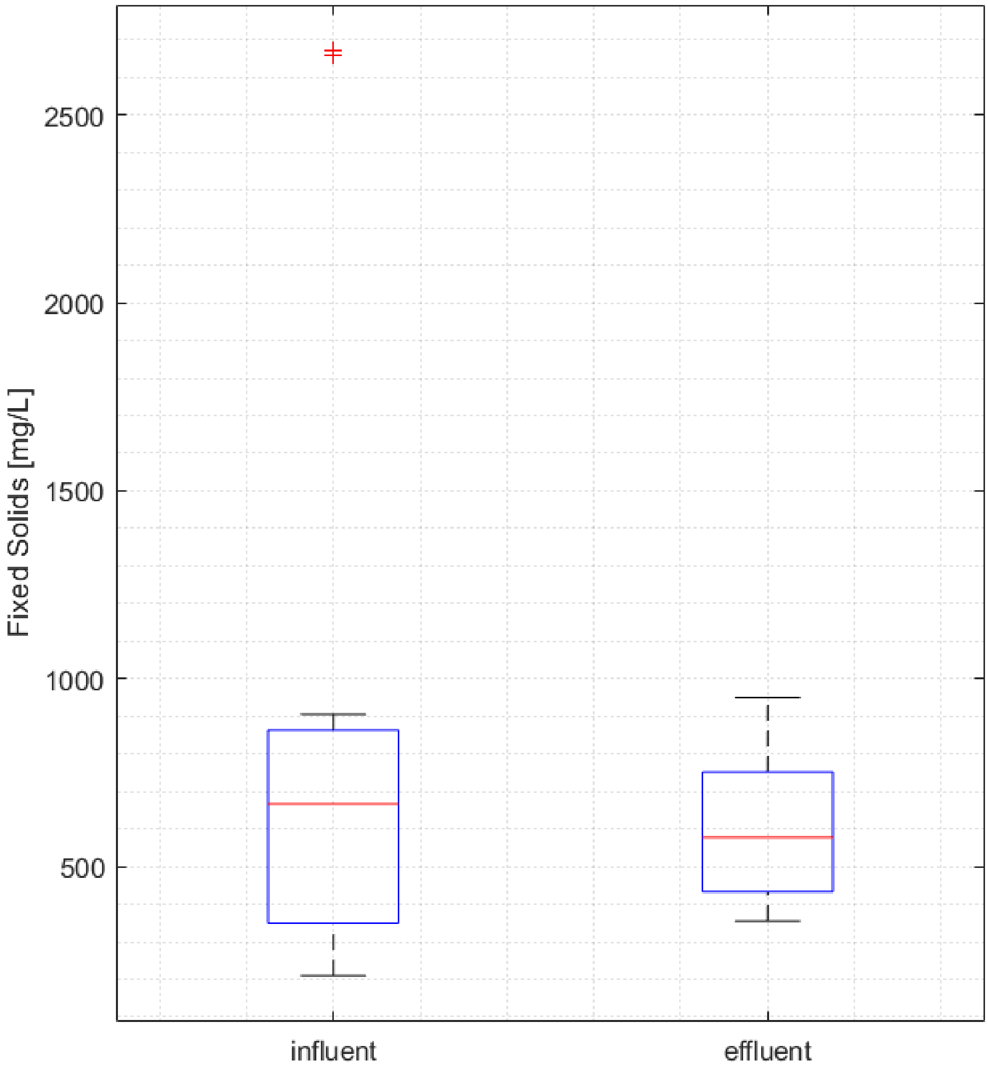

Figure 29: Graphical representation of the occurrence of fixed solids during period 2. The red line indicates the median while the blue box top limit indicates the 75th percentile and the bottom limit the 25th percentile. The whiskers represent the extreme data points that are not considered outliers. The outliers are marked with a red (+).

Total Nitrogen

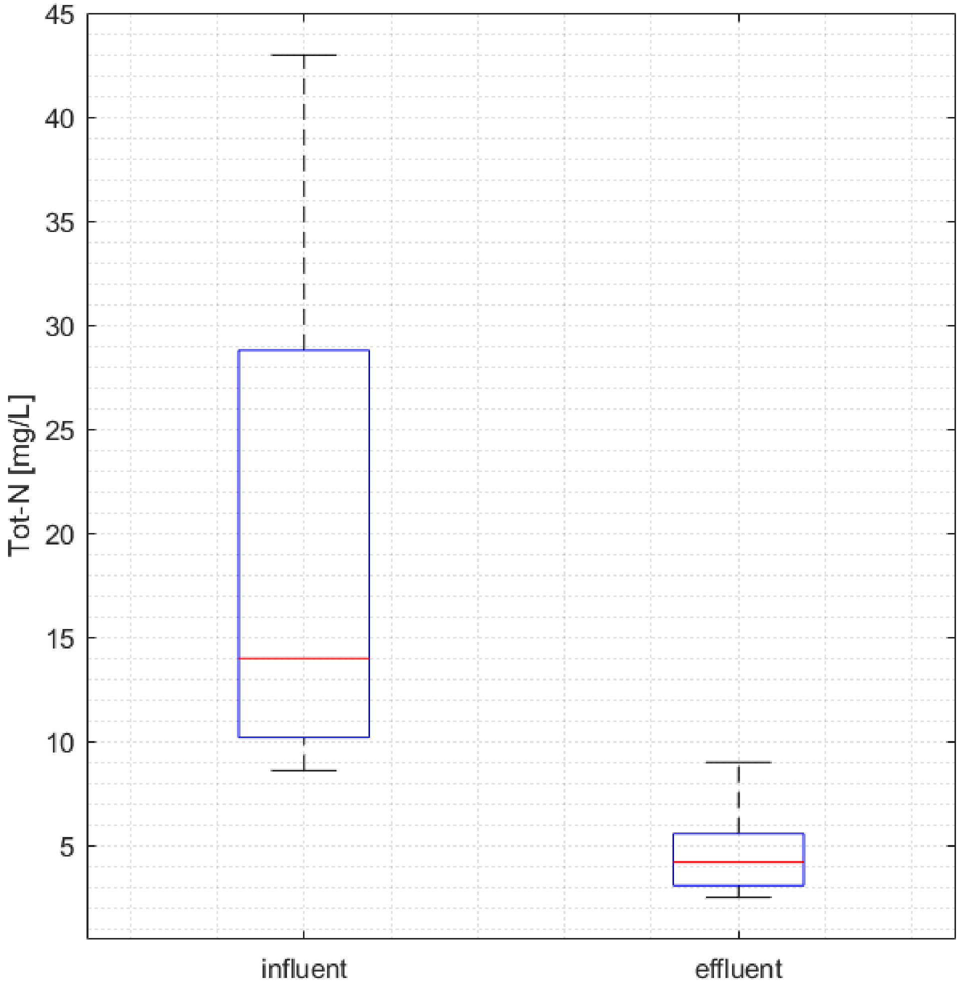

Figure 30: Graphical representation of the occurrence of Total-Nitrogen measured during period 3. The red line indicates the median while the blue box top limit indicates the 75th percentile and the bottom limit the 25th percentile. The whiskers represent the extreme data points that are not considered outliers. The outliers are marked with a red (+).

Total Phosphorus

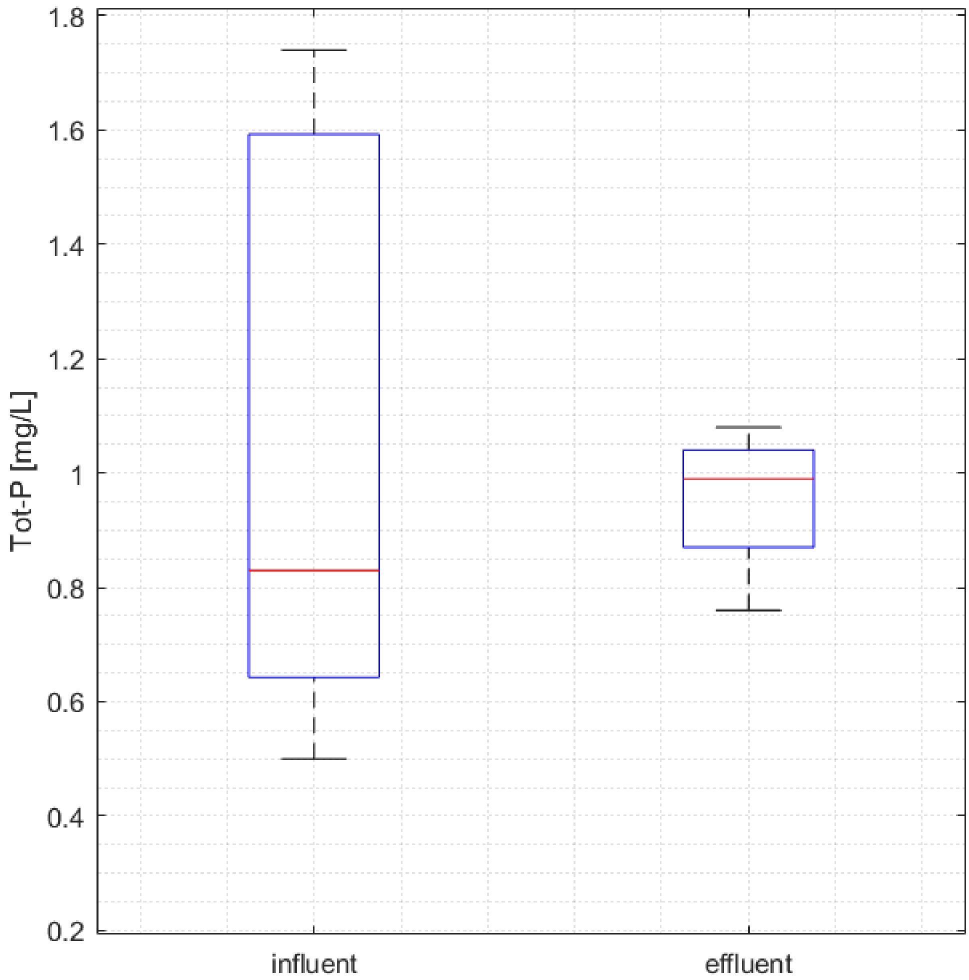

Figure 31: Graphical representation of the occurrence of Total-Phosphorus measured during period 3. The red line indicates the median while the blue box top limit indicates the 75th percentile and the bottom limit the 25th percentile. The whiskers represent the extreme data points that are not considered outliers. The outliers are marked with a red (+).

Appendix C

Sampling schedule for period 2.

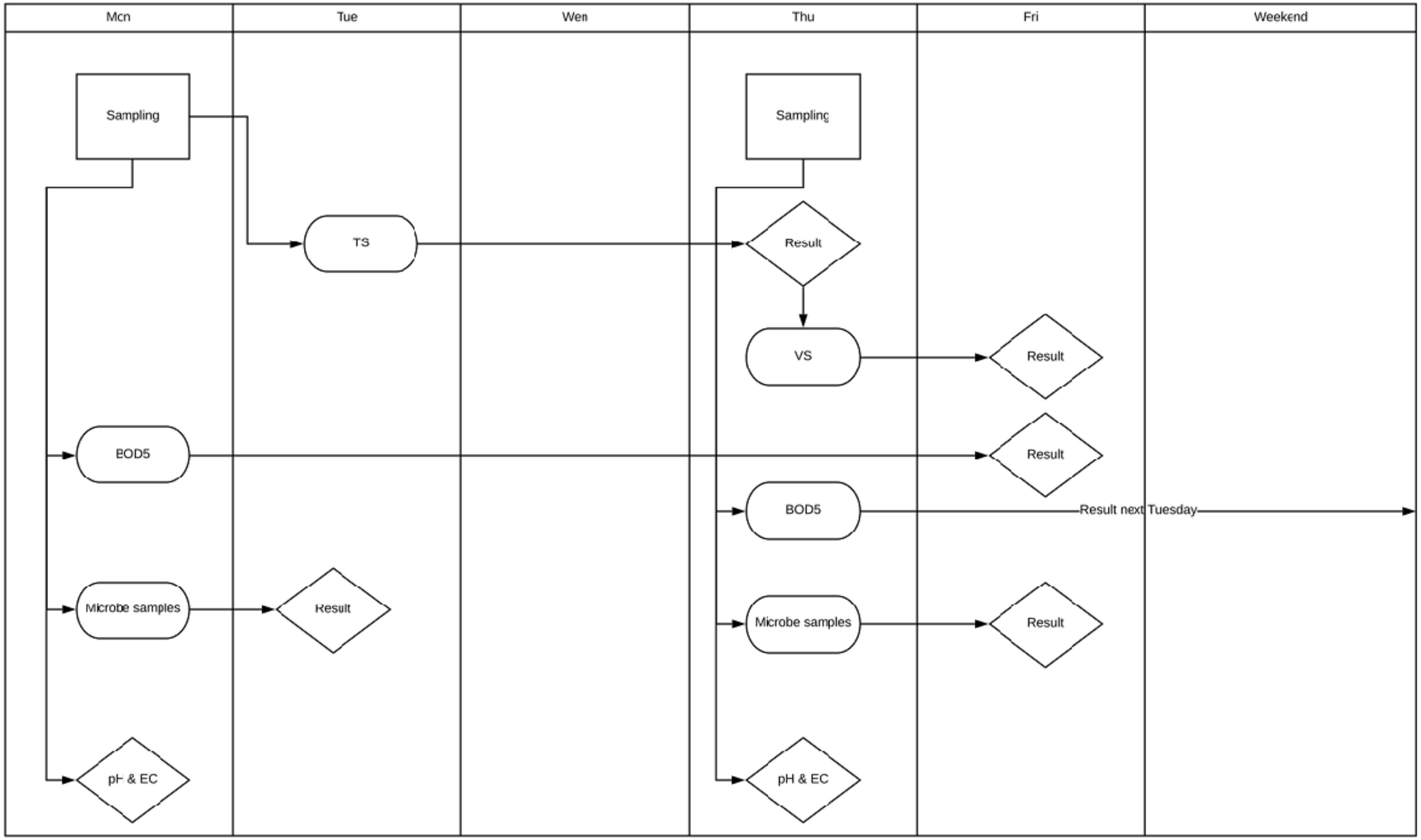

Figure 32: Example schedule for a week of sampling and analyses during period 2. Figure made by Author.

Appendix D

Sample point

Figure 33: Visual difference of the sample collection point when it's not flooeded (left), and when it's flooded with runoff after heavy rainfall (right).