Sustainable Greywater Treatment and Reuse for Irrigation in Rural Tanzania

A Case Study of Tumaini Open School

Master's Thesis in Infrastructure and Environmental Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY

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School building on Tumaini Open School campus
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ABSTRACT

Climate change is expected to intensify water scarcity and increase pressure on water and food security, highlighting the need for alternative water sources for agricultural irrigation. Tumaini Open School in Tabora, Tanzania, experiences water scarcity and unreliable water supply, while greywater is currently discharged directly into the environment. This project investigated the potential for treating and reusing greywater for irrigation at the school through a system adapted to the local context.

The total weekly greywater generation was estimated to be 6000 L/week in Area I (student area) and 3400 L/week in Area III (staff area) based on questionnaires and volumetric measurements. Laundry and shower greywater contributed the largest share of the total greywater generation. Water quality assessment showed that laundry greywater was the most contaminated source in both areas particularly with respect to turbidity and electrical conductivity (EC). A prototype was constructed and operated for 15 consecutive days in order to evaluate the feasibility of a sand filter in terms of treatment performance. The prototype reduced average turbidity of kitchen greywater from 261 to 19 FNU, indicating effective removal of suspended particles. However, EC increased from 494 to 796 μS/cm after treatment, suggesting that dissolved salts were not removed by the filter. A social acceptance questionnaire indicated positive attitudes towards greywater reuse, especially with sufficient information and training prior to implementation.

Based on the results from the volumetric measurements, prototype performance and water quality assessment, a treatment system was proposed. A septic tank followed by an intermittent sand filter (ISF) was dimensioned for Area I and Area III. The treatment system was estimated to provide sufficient treatment with regards to *E. coli* and human health risks based on quantitative microbial risk assessment (QMRA). Overall, the study indicates that greywater reuse has the potential to completely replace municipal water for irrigation during the wet season and reduce municipal water demand by approximately 85% during the dry season.

Key words: Water scarity; Rural; Greywater treatment; Greywater reuse; Irrigation; Quantitative microbial risk assessment; Intermittent sand filter

Hållbara system för rening och återanvändning av gråvatten för bevattning i landsbygdsområden i Tanzania
En fallstudie av Tumaini Open School

Examensarbete inom masterprogrammet Infrastruktur och Miljöteknik

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SAMMANFATTNING

Klimatförändringarna förväntas intensifiera vattenbristen och hota vatten- och livsmedelssäkerheten, vilket ökar behovet av alternativa vattenkällor för bevattning inom jordbruket. Tumaini Open School i Tabora, Tanzania, har begränsad tillgång till vatten och en opålitlig vattenförsörjning, samtidigt som gråvatten idag släpps ut direkt i miljön. Detta projekt undersökte potentialen att återanvända och behandla gråvatten för bevattning vid skolan genom en lösning anpassad till den lokala kontexten.

Baserat på enkäter och volymmätningar uppskattades gråvattenproduktionen till 6000 L/vecka i Area I (studentområdet) och 3400 L/vecka i Area III (personalområdet). Gråvatten från tvätt och dusch utgjorde den största delen av den totala gråvattenproduktionen. Vattenkvalitetsanalysen visade att gråvatten från tvätt var den mest förorenade källan i båda områdena, särskilt med avseende på turbiditet och elektrisk konduktivitet (EC). En prototyp konstruerades och drevs under 15 sammanhängande dagar för att utvärdera sandfiltrets tekniska genomförbarhet och reningsförmåga. Prototypen reducerade den genomsnittliga turbiditeten i köksgråvatten från 261 till 19 FNU, vilket indikerar en effektiv avskiljning av suspenderade partiklar. Däremot ökade EC från 494 till 796 μS/cm efter behandling, vilket tyder på att lösta salter inte avlägsnades av filtret. En enkätundersökning om social acceptans visade en generellt positiv inställning till återanvändning av gråvatten, särskilt om tillräckligt med information och utbildning ges före implementering.

Baserat på resultaten från de volymetriska mätningarna, prototypens reningsförmåga och vattenkvalitetsanalysen föreslogs ett behandlingssystem. En septisk tank följt av ett intermittent sandfilter (ISF) dimensionerades för Area I och Area III. Behandlingssystemet uppskattades ge tillräcklig rening med avseende på *E. coli* och hälsorisker, baserat på kvantitativ mikrobiell riskbedömning (QMRA). Studien visar på att återanvändning av gråvatten på skolan har potential att helt ersätta kommunalt vatten för bevattning under regnperioden, samt minska behovet av det kommunala vattnet med cirka 85% under torrperioden.

Nyckelord: Vattenbrist; Landsbygd; Gråvattenbehandling; Återanvändning av gråvatten; Bevattning; Kvantitativ mikrobiell riskbedömning (QMRA); Intermittent sandfilter

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Preface

This master's thesis was conducted during the spring 2026 at Chalmers University of Technology in the department of Architecture and Civil Engineering. It was conducted in collaboration with Engineers Without Borders Sweden and included 9.5 weeks of field studies at the case study site in Tabora, Tanzania.

We are sincerely grateful for the funding received from the Global Mentorship Program and the Kullman family. Without their support, the field studies and this project would not have been possible.

Special thanks are also extended to our supervisor, Jesper Knutsson. His willingness to make time for us when challenges occured and to provide additional supervision when needed, have been invaluable throughout this project. We would like to acknowledge Amir Saeid Mohammadi for providing laboratory equipment for the field studies and thank him for his assistance in interpreting the results. We would also like to thank our examiner, Frank Persson, for his support from the very beginning and for providing valuable guidance when we first became involved in the project.

We are also very grateful for the opportunity to conduct this project in collaboration with Engineers Without Borders Sweden and for their support, particularly in relation to the field studies. Their guidance throughout the project and experience of working in different contextual settings have been invaluable in helping us assess the feasibility of the project. A special thank you is extended to Jamie Wilton, who on numerous occasions made himself available to discuss the project's progress and ensure that we were well supported throughout the process.

Lastly, we would like to extend our heartfelt thanks to everyone at Tumaini Open School. We are especially grateful to the students for sharing their insights with us and for all the memorable moments we shared. We would also like to thank the headmaster, Ezekiel Kassanga, and the coordinator, Johan Godlove, for their constant support, generosity, and assistance in making this project possible.

Gothenburg, June 2026
Yasmine Jakobsson
Johanna Löf

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List of acronyms

BOD	Biological oxygen demand
BV	Bed volumes
COD	Chemical oxygen demand
DALY	Disability-adjusted life year
EBCT	Empty bed contact time
EC	Electrical conductivity
EWB-SWE	Engineers Without Borders Sweden
FAO	Food and Agriculture Organization
GAC	Granular activated carbon
HLR	Hydraulic loading rate
HRT	Hydraulic retention time
ISF	Intermittent sand filter
LRV	Log reduction value
QMRA	Quantitative microbial risk assessment
SAR	Sodium adsorption ratio
SODIS	Solar disinfection
TDS	Total dissolved solids
TN	Total nitrogen
TP	Total phosphorus
TSS	Total suspended solids
VFCW	Vertical flow constructed wetland
WHO	World Health Organization

1 Introduction

Global warming has been linked to an increase in climate extremes, including heat-waves and prolonged droughts (IPCC, 2023). These changes are caused by increased greenhouse gas emissions driven by unsustainable consumption, which have significant impacts on ecosystems, biodiversity and human societies. (Dore, 2005; Haile et al., 2020; Hussein, 2011). By the end of the century, the global mean temperature is expected to increase by $2.2 - 3.5$°C, under current implemented policies (IPCC, 2023). East Africa is projected to experience more rapid warming than the global average (Choi et al., 2023). Moreover, the region is expected to be particularly affected by intensified water cycles, where climate variability and extreme weathers will further intensify water scarcity (IPCC, 2023). East Africa is particularly vulnerable to climate change due to existing water scarcity and limited resources (Choi et al., 2023). Consequently, climate change may further increase setbacks in socio-economic development and negatively affect both water and food security (Hussein, 2011; IPCC, 2023).

One potential solution to address water scarcity and improve food security is the reuse of wastewater for agricultural irrigation (Food and Agriculture Organization of the United Nations, 2003; World Health Organization, 2006b). Greywater is defined as domestic wastewater excluding toilet effluent, and is therefore less polluted compared to general wastewater (Eriksson et al., 2002; Li et al., 2009). However, greywater must be adequately treated prior to irrigation in order to reduce potential human health risks and environmental impacts (Food and Agriculture Organization of the United Nations, 2003).

Decentralized greywater treatment systems are presenting a low-cost alternative to centralized treatment systems, especially in rural areas (U.S. EPA, 2002). A wide range of greywater treatment systems have been proposed in the literature, including physical, chemical, and biological treatment processes (Li et al., 2009). In addition, decentralized treatment systems can be constructed using locally available materials and adapted to the local context (Niwagaba et al., 2014; Patil et al., 2022).

However, centralized treatment systems generally has a higher acceptance compared to decentralized treatment systems (U.S. EPA, 2002). In addition, the success of implementing a decentralized treatment system is highly dependent on public awareness and acceptance (Jamrah et al., 2006).

Despite the increasing interest in greywater reuse for irrigation, the implementation of decentralized treatment systems in rural and low-resource settings are limited. Rural conditions require solutions customized to the local context, especially when resources are limited. Therefore, treatment systems must be adapted to the environment, technical and societal conditions at the site.

Tumaini Open School, located in rural Tanzania, experiences water scarcity, unreliable water supply, and increasing irrigation demands, motivating the investigation of a decentralized greywater treatment and reuse system.

1.1 Aim

The aim of this project is to address water scarcity at Tumaini Open School and reduce the reliance on municipal water supply through the development of a greywater treatment and reuse system. The proposed solution should be adapted to the site-specific conditions, and enable safe reuse of treated greywater for irrigation purposes at the school. In addition, the treated greywater must be of sufficient quality to fulfil relevant requirements related to safe irrigation reuse and protection of human health.

1.2 Research questions

The master's thesis aims to address the following research questions:

1. Where is greywater generated at the school, in what quantities, and what are the water quality characteristics of the different greywater sources?
2. How do students and staff at the school perceive greywater reuse for irrigation purposes?
3. What type of greywater treatment and reuse system is most suitable for the local conditions and future needs at Tumaini Open School to address irrigation needs?
4. Can the proposed treatment system provide treated greywater of sufficient quality for safe crop irrigation with respect to human health risks?

1.3 Limitations

The study is subject to several limitations, particularly regarding the fieldwork conducted at the site. The duration of the field studies were limited to 9.5 weeks during the rainy season (February to April 2026). Consequently, all collected data reflect the conditions during this specific period. During the dry season, conditions at the school differ significantly, with more frequent water shortages, reduced agriculture, and less rainfall. These factors are expected to influence both greywater generation and other collected data. Therefore, the measured data cannot be considered fully representative of the entire year. Furthermore, the rural setting presented limitations regarding both material availability and analytical equipment. Therefore, only parameters measured using the equipment brought from Sweden could be analysed. This limited the extent of the water quality characterization, and several parameters were instead estimated and discussed based on literature values.

2 Theory

This chapter presents the compiled relevant theory that provides the basis for the study.

2.1 Greywater

Greywater is considered domestic wastewater originating from bathrooms, including hand basins and showers, kitchen activities such as dishwashing and kitchen sinks, as well as from laundry, while excluding wastewater from toilets (Eriksson et al., 2002; Jefferson et al., 2004). The term greywater originates from the observation that the water turns grey when stored without treatment (Jamrah et al., 2006).

Greywater reuse is becoming an increasingly important component of water reuse strategies to address water scarcity caused by factors such as limited rainfall or increasing water demand (Eriksson et al., 2002; Jefferson et al., 2004). Greywater is well suited for reuse compared to blackwater from toilets, as it is less contaminated due to lack of faeces, urine, and toilet paper, and contains lower concentrations of nitrogen (Eriksson et al., 2002; Jamrah et al., 2006).

Greywater can be reused for non-potable purposes such as toilet flushing, irrrigation, vehicle washing, concrete production and fire protection (Jefferson et al., 2004). Such reuse can provide environmental benefits, including reduced pressure on freshwater resources and decreased downstream pollution from the point of discharge (World Health Organization, 2006a). However, some risks related to greywater reuse are also of concern (Eriksson et al., 2002). Microorganisms may be transmitted and cause health risks when greywater is reused for irrigation or toilet flushing. When greywater is reused for irrigation, both the soil and receiving waters may be affected, as well as the plants being irrigated. This highlights the need to properly characterize greywater and to develop sufficient treatment solutions.

2.1.1 Greywater quantity

The amount of greywater produced in a household depends largely on the practices and conditions in the specific context. Table 2.1 presents reported ranges of greywater generation identified across multiple sources and contexts. Greywater generation rates vary considerably worldwide, ranging from approximately 14 to 225 L per person per day. This variation depends on factors such as living standards, number of occupants, age, gender, and access to water (Ghaly, Emam, et al., 2021; Li et al., 2009; Uthirakrishnan et al., 2022). In developing countries experiencing water scarcity and poverty, greywater generation is typically at the lower end of the reported range and rarely exceeds 100 L per person per day. (Uthirakrishnan et al., 2022; World Health Organization, 2006a)

Based on the total water consumption, it is possible to estimate the share of greywater. Studies report ranges of approximately 50–85% of the total water consumption becoming greywater, as shown in Table 2.1. A study from Addis Ababa in Ethiopia reported that around 50% of water consumption becomes greywater (Tusiime et al., 2022). Another study conducted in Amman, Jordan, found the greywater share to be approximately 70% (Jamrah et al., 2006). Whereas an additional study from Uganda conducted by Katukiza et al., 2015 found the greywater share to be 85% of the total water consumption. The difference between the reported values reflect contextual differences between the study areas, such as variations in water availability and household water use practices.

Table 2.1: Reported greywater generation volumes and relative contributions based on literature data.

Parameter	Reported range	Unit	References
Greywater generation	14–225	L person^{-1} day^{-1}	(Ghaly, Emam, et al., 2021; Tusiime et al., 2022; Uthirakrishnan et al., 2022)
Greywater share of total water consumption	50–85	%	(Jamrah et al., 2006; Katukiza et al., 2015; Tusiime et al., 2022)

2.1.2 Greywater quality

The contaminant load of greywater is strongly shaped by both technical and behavioural factors, including water supply quality, characteristics of the distribution network, and chemical and biological transformations occurring during transport and storage (Oteng-Peprah et al., 2018). At the household level, water-use practices, the types of chemicals used for laundry, cleaning, and showering, as well as seasonal variations in behaviour, influence greywater quality. Furthermore, internal variability between household greywater sources has been observed, with kitchen and laundry greywater generally exhibiting higher levels of organic and physical pollutants, while bathroom greywater shows lower contamination levels (Bakare et al., 2017; Edwin et al., 2013; Ghaly, Emam, et al., 2021; Li et al., 2009).

Greywater is characterized by physico–chemical parameters such as pH, temperature (Temp.), turbidity (Turb), suspended solids (TSS) and electrical conductivity (EC) (Tusiime et al., 2022). Typical ranges of greywater parameters, from several studies are compiled in Table 2.2.

The pH of greywater have been reported to range between 5.43 and 9.82 as seen in Table 2.2, and is influenced both by the water supply characteristics and the greywater source (Oteng-Peprah et al., 2018). The supply network affects greywater quality through the alkalinity and pH of the incoming water. In addition, the type of greywater source and household practices influence pH levels, particularly through cleaning and washing activities. Since soaps and detergents are often alkaline, greywater generated from laundry and bathing activities tends to exhibit elevated pH levels (Bakare et al., 2017; Oteng-Peprah et al., 2018). This pattern is supported by findings from a study conducted in South Africa, where laundry and bath greywater showed higher pH values, while kitchen greywater exhibited the lowest pH (Bakare et al., 2017). The lower pH in kitchen greywater may be explained by the fact that it was mainly contaminated with food residues and oils, which can promote faster degradation.

Table 2.2: Reported greywater characteristics based on ranges presented in the literature.

Parameter	Reported range	Unit	References
pH	5.43–9.82	–	(Ghaly, Emam, et al., 2021; Niwagaba et al., 2014; Uthirakrishnan et al., 2022; Zipf et al., 2016)
Temp.	18–38	°C	(Ghaly, Emam, et al., 2021; Tusiime et al., 2022; Uthirakrishnan et al., 2022)
TSS	23–1396	mg/L	(Ghaly, Emam, et al., 2021; Tusiime et al., 2022; Uthirakrishnan et al., 2022)
Turb.	20–619	NTU	(Edwin et al., 2013; Subramanian et al., 2020; Uthirakrishnan et al., 2022)
EC	300–3 000	μS/cm	(Ciabattia et al., 2009; Ghaly, Emam, et al., 2021; Niwagaba et al., 2014)
TDS	102–1 100	mg/L	(Niwagaba et al., 2014; Oteng-Peprah et al., 2018; Tusiime et al., 2022)
COD	47–643	ppm	(Subramanian et al., 2020; Zipf et al., 2016)
BOD	35–445	ppm	(Subramanian et al., 2020; Zipf et al., 2016)
TP	0.11–48	mg/L	(Uthirakrishnan et al., 2022)
TN	1.7–153	mg/L	(Ghaly, Emam, et al., 2021; Niwagaba et al., 2014; Uthirakrishnan et al., 2022)

Note: Reported ranges represent the minimum and maximum values identified across multiple studies and are included to illustrate the variability of greywater characteristics across different contexts.

The temperature of greywater varies considerably, with reported values in the literature ranging from 18–38 °C (Table 2.2), primarily influenced by kitchen and bathroom sources. During storage, greywater may undergo chemical and biological degradation, with higher temperatures enhancing microbial growth in the presence of organic matter and nutrients from household sources (Tusiime et al., 2022).

Total suspended solids (TSS) concentrations in greywater vary considerably depending on the source and local context. Reported values in the literature range from 23 to 1 396 mg/L (see Table 2.2). Total suspended solids are more present in laundry and kitchen greywater due to activities such as washing and food preparations, which introduce particulate matter into the greywater (Li et al., 2009; Oteng-Peprah et al., 2018). Suspended solids are a key parameter in greywater treatment for reuse, as elevated concentrations are associated with microbial contamination (Li et al., 2009).

Turbidity has been reported to range from 20 to 619 NTU, see Table 2.2. Turbidity is influenced by the water activity, where kitchen and laundry water contain higher contents of suspended matter and therefore becomes more turbid (Oteng-Peprah et al., 2018). Turbidity reflects the presence of suspended and colloidal material in greywater (Eriksson et al., 2002). Elevated turbidity levels may increase the risk of operational issues such as clogging, particularly in distribution systems and filtration units.

Important to note is that turbidity can be measured using different technologies and is therefore reported in different units (Kitchener et al., 2017), commonly used ones are NTU (Nephelometric Turbidity Units) and FNU (Formazin Nephelometric Units). Since different instruments are used, they are not directly comparable. However, WHO suggests that the two units are considered approximate equivalent despite the different measurement approaches(World Health Organization, 2017).

Electrical conductivity (EC) provides an indication of the total concentration of dissolved ions, which influence the salinity of the water (Bakare et al., 2017). Reported values are ranging from 300 to 3000 μS/cm, as seen in Table 2.2. Dissolved materials and poor plumbing materials can increase the EC in the greywater (Oteng-Peprah et al., 2018). Furthermore, greywater originating from the bathroom has lower values compared to kitchen and laundry according to the study conducted by Bakare et al., 2017. Therefore, bath water is more suitable for irrigation reuse, since high electrical conductivity can adversely affect plants and lead to long-term salt accumulation in the soil.

Total dissolved solids (TDS) represent the total concentration of dissolved inorganic and organic substances present in greywater, including salts, minerals, and small amounts of organic matter (Dewangan & Shrivastava, 2024). TDS is closely related to electrical conductivity (EC), as both parameters are governed by the concentration of dissolved ions in the water. However, the relationship between EC and TDS is not fully constant and may vary depending on the composition of the dissolved substances. Reported TDS concentrations in greywater range from 102 to 1 100 mg/L, see Table 2.2. Elevated TDS levels are typically associated with greywater from kitchen and laundry sources due to the presence of detergents, cleaning agents, and dissolved food residues (Oteng-Peprah et al., 2018).

Chemical parameters such as chemical oxygen demand (COD), biological oxygen demand (BOD), total phosphorus (TP) and total nitrogen (TN) have displayed ranges in Table 2.2. COD measures the amount of oxygen needed to chemically oxidise organic matter in water (Bakare et al., 2017). Since certain organic compounds can be chemically oxidized but are not biologically degradable, the measured COD value is typically higher than BOD in wastewater. (Bakare et al., 2017). The BOD/COD ratio is therefore commonly used to assess the biodegradability of greywater, and indicates how easy microorganisms can degrade the organic matter. A BOD/COD ratio of approximately 0.5, or higher, represents good potential for biological treatment (Bakare et al., 2017; Edwin et al., 2013; Katukiza et al., 2015; Li et al., 2009).

A literature review conducted by Li et al. (2009) concluded that all types of greywater exhibit good biodegradability. However, as shown in Table 2.3, reported BOD/COD ratios range from approximately 0.12 to above 0.6, illustrating substantial variability between studies. While several sources report values indicating good biodegradability, others suggest limited suitability for biological treatment. This variation highlights the influence of contextual factors such as source composition and household practices.

Table 2.3: Reported BOD/COD ratios for greywater from different household sources.

Bathroom	Kitchen	Laundry	Location	Source
0.31	0.33	0.24	Kampala, Uganda	(Katukiza et al., 2015)
0.13	0.29	0.25	Durban, South Africa	(Bakare et al., 2017)
0.385*	0.833*	0.120*	India	(Edwin et al., 2013)
0.641*	0.641*	0.641*	Kampala, Uganda	(Niwagaba et al., 2014)

* Values converted from reported COD/BOD ratios using the inverse relationship (BOD/COD = 1/(COD/BOD)).

Faecal contamination in greywater is primarily derived from human activities, such as showering and washing contaminated clothing, including diapers (World Health Organization, 2006a). Other pathogenic microorganisms, such as *Salmonella* and *Campylobacter*, may originate from kitchen activities and inadequate food handling practices. Biological parameters related to fecal contamination can be assessed using indicator organisms such as *E. coli*.

However, traditionally used indicator organisms can lead to overestimations of contamination levels (World Health Organization, 2006a). Greywater typically contains readily degradable organic compounds, which can stimulate the growth of indicator organisms. Therefore, coprostanol has been suggested as an alternative indicator to reduce the risk of overestimating fecal contamination (Ottoson & Axel Stenstr om, 2003).

Table 2.4 shows reported values of microbial concentrations from different contexts. According to the findings, higher concentrations of microorganisms have been reported in studies from low- and middle-income countries compared to high-income countries, highlighting contextual variations in microbial contamination of greywater.

Table 2.4: Reported concentrations of microbial contamination in greywater in cfu/100 mL.

Type	Parameter	Value	Context	Source
Greywater	*E. coli*	2.84×10^7	Burkina Faso	(Maiga et al., 2024)
Laundry	*E. coli*	1.44×10^6	Uganda	(Katukiza et al., 2015)
Bathroom	*E. coli*	2.35×10^6	Uganda	(Katukiza et al., 2015)
Kitchen sink	*E. coli*	7.0×10^5	Jordan	(Halalsheh et al., 2008)
Greywater	*E. coli*	6.0×10^5	Jordan	(Halalsheh et al., 2008)
Greywater	*E. coli*	$5.0 - 8.6 \times 10^3$	New Zealand	(Leonard et al., 2016)
Greywater	*E. coli*	2.022×10^3	England	(Jefferson et al., 2004)
Greywater	Fecal coliforms	2.15×10^9	Burkina Faso	(Maiga et al., 2024)
Laundry	Total coliforms	7.15×10^7	Uganda	(Katukiza et al., 2015)
Kitchen	Total coliforms	5.87×10^7	Uganda	(Katukiza et al., 2015)
Bathroom	Total coliforms	1.07×10^8	Uganda	(Katukiza et al., 2015)
Laundry	*Salmonella* spp.	5.74×10^5	Uganda	(Katukiza et al., 2015)
Bathroom	*Salmonella* spp.	1.94×10^5	Uganda	(Katukiza et al., 2015)

2.2 Greywater treatment

Greywater treatment systems employ physical, chemical, and biological processes to reduce pollution (Ghaly, Emam, et al., 2021). Physical treatment includes separation of contaminants via methods such as filtration and sedimentation. Filtration removes suspended solids by passing the water through porous media such as sand or gravel (Hakami et al., 2020). Sedimentation relies on gravity to allow heavier particles to settle in a tank or settling chamber (Ghaly, Emam, et al., 2021). Chemical treatment involves the addition of substances like disinfectants and coagulants to reduce pollutants and enhance particle removal. Biological treatment utilizes microorganisms to degrade and transform greywater constituents through biochemical reactions (Ghaly, Abdelrahman, et al., 2021).

The following sections review design parameters and treatment technologies relevant for greywater treatment and reuse. Particular emphasis is placed on technologies suitable for rural and resource-limited settings, with a focus on decentralized, low-cost systems that can be constructed, operated, and maintained using locally available resources.

2.2.1 Hydraulic design parameters

Hydraulic loading rate (HLR) is the volume of wastewater applied per unit surface area of the treatment system and is defined as the influent flow divided by the surface area of the filter according to Equation 2.1 (Dotro et al., n.d.).

$$HLR = \frac{Q}{A} \tag{2.1}$$

where:

- HLR = hydraulic loading rate [L/m^2/d]
- Q = Influent flow [m^3/d]
- A = Surface area of the filter [m^2]

In general, higher hydraulic loading rates may result in lower effluent quality (U.S. EPA, 1999). Higher hydraulic loading rates may be applied when the filter media has a larger grain size or when the influent water contains relatively low contaminant concentrations. Lower hydraulic loading rates have been found to promote improved bacterial removal in soil-based treatment systems, as they favour unsaturated flow conditions and increase contact between wastewater and the filter media (U.S. EPA, 2002).

Hydraulic retention time (HRT) is another key design parameter in wastewater treatment systems, as it directly influences the contact time between water and treatment media, thereby affecting removal processes (Ghaly, Emam, et al., 2021). HRT is the average time required for a water parcel to pass through the treatment system (Dotro et al., n.d.). It is traditionally calculated as the ratio between the effective volume of the treatment system and the influent flow rate as in equation 2.2:

$$HRT = \frac{V}{Q} \tag{2.2}$$

where:

- HRT = hydraulic retention time [d]
- V = effective reactor volume [m^3]
- Q = influent flow rate [m^3/d]

The hydraulic retention time required varies depending on factors such as the type of treatment system, the filter media used, and the local context (Niwagaba et al., 2014; Tusiime et al., 2022; Uthirakrishnan et al., 2022). The calculated retention time can also differ significantly from the actual HRT due to short-circuiting within the tank (U.S. EPA, 1995).

While HRT is commonly used for reactor-based systems, adsorption filters are often characterized using the empty bed contact time (EBCT), which describes the theoretical contact time between the water and the filter media (U.S. EPA, n.d.). EBCT is used to determine the carbon depth and the sorption capacity when dimensioning the filter. It is defined as the empty bed volume divided by the inflow through the filter media according to equation 2.3.

$$EBCT = \frac{V_{bed}}{Q} \tag{2.3}$$

where:

- EBCT = empty bed contact time (EBCT), [h]
- V_{bed} = volume of the filter bed, [m^3]
- Q = influent flow rate, [m^3/h]

2.2.2 Treatment technologies

A wide range of treatment technologies have been investigated for decentralized greywater treatment, varying in complexity, treatment mechanisms, and operational requirements (Ghaly, Emam, et al., 2021). This section presents different treatment technologies that are feasible within resource-limited settings.

2.2.2.1 Septic tanks

A septic tank is an enclosed, buried tank that receives wastewater for pre-treatment (US EPA, 1980). They are commonly used as a pre-treatment prior to, for instance a constructed wetland or a sand filter (**Bounds1997DesignTank**). It separates solids from the liquid through sedimentation which accumulates at the bottom as sludge (US EPA, 1980). Lighter materials, such as grease and fats, form a scum layer at the surface. The treated liquid is diverted out of the tank at an outlet located above the sludge layer and below the scum layer.

A septic tank can consist of either a single compartment or multiple compartments (US EPA, 1980). Even when having the same total capacity, multi-compartment tanks generally achieve higher effluent quality, as they improve sedimentation and reduce suspended solids in the effluent. This becomes especially important during periods of high inflow of wastewater.

The tank should ideally operate close to plug flow conditions with a sufficient hydraulic retention time (HRT) to allow particles to either settle or float (**Bounds1997DesignTank**). A plug flow can be achieved by placing baffles inside the tank, which also will decrease turbulence. (US EPA, 1980).

In addition to physical separation processes, anaerobic biological processes also occur passively within the tank due to naturally occurring microorganisms in the wastewater (**Bounds1997DesignTank**). However, the establishment of a stable and efficient biological treatment process may take time, particularly during the start-up phase of the system. Therefore, the tank should be sufficiently sized to provide relatively undisturbed conditions over time, allowing microorganisms to establish and support the biological digestion processes within the tank.

The treatment efficiency of septic tanks are as previously mentioned related to number of compartments, the flow regime and the size of the tank. However, the design of the inlet and outlet, temperature of the water and operation and maintenance are also affecting the performance (US EPA, 1980).

Maintenance needs include pumping out sludge, which for general wastewater tanks should be every 3–5 years (US EPA, 1980). When sludge is pumped out, no cleaning of the tank is necessary. An increased sludge depth will negatively affect the treatment efficiency due to shorter HRT in the tank. Additionally, the tank should be inspected to evaluate the actual accumulation of both sludge and scum. By doing this, it is possible to determine the actual needed inspection and pumping frequency. Additional structures on the tank also require inspection and cleaning in order for the tank to operate efficiently. Septic tanks are long-lasting structures, that with routine maintenance can be in operation for around 50 years.

2.2.2.2 Vertical flow constructed wetlands

Vertical flow constructed wetlands (VFCWs) are a type of subsurface flow system where water vertically percolates through the filter media (Uthirakrishnan et al., 2022). A common configuration consists of a top layer with vegetation, often referred to as macrophytes, followed by layers of sand and gravel with varying grain sizes (Ghaly, Emam, et al., 2021). The vegetation contributes to the treatment process by stabilizing the substrate, promoting oxygen transfer through the root zone, and providing surface area for microbial growth (U.S. EPA, 1995). Beneath the planted layer, finer filter media are typically used for filtration and pollutant removal, while coarser gravel layers at the bottom function as drainage and support layers for water collection (Hoffmann et al., 2011; U.S. EPA, 1995).

In VFCWs, wastewater is intermittently pumped onto the wetland surface, typically 4–12 times per day, to allow periods of aeration between loading cycles (Hoffmann et al., 2011). The influent should be evenly distributed across the wetland bed through properly designed distribution pipes. Typical designs include a sand filter layer of at least 50 cm, underlain by a gravel drainage layer of at least 20 cm and covered by a top gravel layer of approximately 10 cm. Hydraulic loading rates are commonly limited to 200 mm/d of pre-treated wastewater, although temporary peak loads of up to 500 mm/d during rainfall events can be tolerated.

VFCWs are highly effective in removing suspended solids and organic matter, with removal efficiencies commonly reported between 90–99% (Hoffmann et al., 2011). To maintain treatment performance and prevent clogging, sufficient oxygen supply and regular resting periods of the beds are essential, as these allow temporary clogging to reverse and support continued aerobic degradation processes.

A VFCW is designed to be a low-maintenance and low-energy treatment system, although regular oversight is still required to ensure proper operation (U.S. EPA, 1995). An operation and maintenance (O&M) plan should include routine inspections to ensure that wastewater is passing sufficiently through the filter bed, as well as maintenance of system structures such as inlets, outlets, and distribution pipes to prevent the accumulation of debris or algae.

The vegetation also requires regular maintenance (U.S. EPA, 1995). Maintaining an appropriate water level is essential, together with frequent mowing and the prevention of shrub growth, tree establishment, and invasive species. Elimination of stagnant water is also important in order to reduce the risk of mosquito breeding. When properly designed and maintained, VFCWs can have a lifespan exceeding 20 years.

2.2.2.3 Sand filtration

In sand filter systems, water percolates through layers of sand and porous materials (Ghaly, Emam, et al., 2021). Water is introduced at the top of the filter and flows vertically through the filter media under gravity before being collected at the bottom of the system. The removal of pollutants occurs through a combination of physical filtration, adsorption, sedimentation, and biological degradation processes (Amankwah et al., 2025).

Sand filtration systems are commonly composed of multiple media layers with different functions (Amankwah et al., 2025; Bautista Quispe et al., 2026). Coarser materials such as gravel are typically used in the lower parts of the filter to facilitate drainage and water collection, while finer media layers are responsible for pollutant removal (Bautista Quispe et al., 2026; Shaikh & Ahammed, 2022).

The treatment efficiency of sand filters is strongly influenced by the depth of the sand (Shaikh & Ahammed, 2022). Studies have shown that a minimum filter depth of approximately 30 cm is generally required to achieve effective removal of physicochemical and microbial contaminants. The upper layers of the filter are typically the most biologically active due to higher oxygen availability and greater concentrations of organic matter, which promote the development of a biofilm near the filter surface. However, this biologically active layer does not develop immediately, as a maturation or ripening period is generally required before stable treatment performance is achieved (Amankwah et al., 2025). How long this maturing takes differs depending on the site specific conditions. A design manual from US EPA, 1980 reports a time interval of a few days up to two weeks for Intermittent sand filters (ISFs).

The biofilm layer is also associated with improved microbial removal efficiency (Shaikh & Ahammed, 2022). Consequently, substantial reductions in turbidity, BOD, COD, and microbial indicators often occur within the upper 10–30 cm of the filter bed, where biological activity is greatest. Deeper layers instead contribute more gradually to additional treatment processes. In these deeper parts of the filter, oxygen availability may become more limited as dissolved oxygen is consumed through microbial degradation and oxidation processes, which can reduce biological activity. Nevertheless, increased filter depth may still contribute to nutrient removal through processes such as simultaneous nitrification and denitrification occurring throughout the filter profile.

Sand filters can be operated under either continuous or intermittent loading conditions. A review by Shaikh and Ahammed (2022) comparing treatment performance in different studies reported that continuously operated filters generally achieved higher removal efficiencies for turbidity, COD, BOD, NH_4-N, PO_4-P, and *E. coli*. For intermittently loaded filters, the resting period between two consecutive feeding cycles has been identified as an important factor influencing treatment performance, with reported pause periods ranging from approximately 1 to 48 hours. These resting periods promote aeration within the filter bed and support aerobic microbial degradation processes. In continuously operated systems, control of the filtration rate is essential to maintain stable hydraulic conditions.

Sand filters may also operate under saturated or unsaturated conditions. Studies have shown that saturated filters often achieve higher overall treatment performance compared to unsaturated filters (Shaikh & Ahammed, 2022). However, saturated filters tend to develop anoxic conditions at greater filter depths, whereas unsaturated filters maintain more aerobic conditions that favour nitrification and enhanced NH_4-N removal.

The hydraulic performance may gradually decrease over time due to clogging caused by the accumulation of suspended solids and fine particles within the filter media (Shaikh & Ahammed, 2022). Filters containing excessively fine media may be particularly susceptible to reduced permeability and surface ponding. Appropriate pre-treatment, media selection, and loading conditions are therefore important to maintain stable operation and prevent excessive clogging.

To restore hydraulic capacity and maintain treatment efficiency, maintenance procedures such as cleaning, replacement of clogged media layers, or backwashing may be required depending on the filter configuration (Shaikh & Ahammed, 2022). Backwashing involves reversing the flow direction through the filter bed with clean water until the entire filter bed is expanded and the backwash water is clear (Ghaly, Emam, et al., 2021).

The operational lifespan of sand filtration systems is largely determined by their ability to maintain both treatment efficiency and hydraulic capacity over time (Hamisi et al., 2024). One of the main factors limiting long-term performance is clogging caused by the accumulation of suspended solids and organic matter within the filter media, which gradually reduces the effective porosity of the filter bed. High organic loading conditions and excessive hydraulic loading rates (HLR) may accelerate clogging by reducing residence time and increasing the accumulation of retained particles within the system.

2.2.2.4 Carbon filters

Carbon filters can either be the main filtration unit or work as a purifying step after other treatments such as sand filters (Environmental Protection Agency, 2020; Niwagaba et al., 2014).

Charcoal as a filter medium functions mainly through adsorption, where pollutants are removed by binding to the surface of the material (Environmental Protection Agency, 2020). In addition, physical filtration also contribute to removal of solids and turbidity reduction within the filter media. It has been shown to be an effective filter medium and a promising alternative to conventional materials such as sand (Tusiime et al., 2022). Carbon filters can achieve high removal efficiencies for organic compounds such as surfactants, as well as reductions in COD, BOD_5, nutrients, and pathogen indicators (Dalahmeh et al., 2012; Environmental Protection Agency, 2020; Tusiime et al., 2022). Furthermore, a study found that charcoal filtration increased the pH of the treated water from slightly acidic conditions to a more neutral or alkaline range (Musa et al., 2020).

Granular activated carbon (GAC) and wood-based charcoal are two types of carbon that can be used in water treatment, although they differ significantly in terms of processing, structure, and cost (Agbanobi, 1999; Mohan & Pittman, 2006). Activated carbon can have a specific surface area from 1000 to 2000 m^2/g (Mohan & Pittman, 2006), compared to sand that had a surface area of 0.136 m^2/g in a study by Dalahmeh et al., 2012. The large specific surface area enhances the adsorption capacity of the material, which makes carbon a suitable material (Environmental Protection Agency, 2020).

Wood-based charcoal can be obtained from residual sources, such as fireplace charcoal or other by-products of wood combustion (Agbanobi, 1999; Niwagaba et al., 2014), which is especially suitable in low-income areas. Before being used in filtration systems, the material is usually crushed, soaked, and sieved into specific particle size fractions (Agbanobi, 1999).

The primary design parameter for carbon filter is the empty bed contact time (EBCT) (Environmental Protection Agency, 2020). The EBCT should not be below 10 minutes and may extend to 30 minutes or more depending on the treatment objectives. Filtration rate and media depth are also two design parameters, however, they are largely influenced by the EBCT. Nevertheless, loading rates are usually around 1.5 m/h and the filter bed depth can range from 2.5–3 m.

The filter can be maintained through backwashing to clean the filter (Environmental Protection Agency, 2020). However, once the adsorption capacity is depleted, the media need to be either regenerated or replaced. The lifetime of a carbon filter depends on the water quality and the purpose of the treatment, where it can range from 9–60 months.

2.2.2.5 Solar disinfection

One commonly applied disinfection method of water is solar disinfection (SODIS), which involves exposing transparent glass or plastic containers filled with water to direct sunlight for a certain period of time, typically at least 6 hours (McGuigan et al., 2012). The UV radiation damages the DNA of pathogens, and most waterborne pathogenic bacteria can be inactivated within this time. Protozoa and viruses are generally more persistent and may require up to 12 hours of direct sunlight exposure for effective inactivation.

SODIS is widely used across more than 50 countries, particularly in low-income regions with high solar radiation (McGuigan et al., 2012). The method is most commonly applied for household drinking water treatment using small transparent plastic or glass bottles, typically with volumes around 2 liters. These containers are inexpensive and easily accessible, making the method highly cost-effective. However, the small treatment volume is a major limitation.

One approach to improve solar disinfection in larger-scale systems is to reduce the water depth and increase the exposed surface area through specialized reactor designs (McGuigan et al., 2012). An example is a pilot-scale SODIS system tested in rural Kenya, where surface water was treated using approximately 120 m of narrow Pyrex tubes positioned within reflectors. The system operated as a continuous-flow reactor with a treatment capacity of 10 L/min and achieved complete coliform removal after approximately 20 minutes of residence time. The use of Pyrex enabled high transmission of UV radiation, allowing more effective pathogen inactivation compared to larger untreated water volumes. However, despite promising treatment performance, the practical application of such systems may be limited by factors including construction complexity, material costs, and operational requirements in low-resource settings.

2.2.3 Filter operation

Filtration systems change over time during operation, as their performance is influenced by loading conditions and the accumulation of material within the filter media (Grace et al., 2016). As water passes through the filter, both suspended and dissolved substances may be retained, altering the physical and chemical conditions within the system (Amankwah et al., 2025). These changes can affect treatment efficiency and lead to variations in effluent quality over time.

To describe the cumulative loading of a filter, the concept of bed volumes (BV) is commonly used (Kukučka et al., 2017). Bed volumes represent the ratio between the total volume of water treated and the volume of the filter bed, as defined in Equation 2.4:

$$BV = \frac{V_{treated}}{V_{bed}} \tag{2.4}$$

where:

- BV = bed volumes [-]
- $V_{treated}$ = cumulative volume of treated water [m^3]
- V_{bed} = volume of the filter bed [m^3]

The use of bed volumes enables comparison of filter performance over time, independent of flow rate or operational duration (Kukučka et al., 2017). As the number of treated bed volumes increases, the filter is progressively exposed to higher cumulative loading, which may influence removal efficiency.

2.3 Irrigation

Surface irrigation is one of the most commonly used irrigation methods and involves the application of water over the soil surface, where it infiltrates into the root zone (Ali et al., 2021). This method is generally simple and requires limited technical infrastructure, but it often results in uneven water distribution and significant water losses through runoff, evaporation, and deep percolation (Sable et al., 2019). In its simplest form, surface irrigation can be carried out manually. In rural contexts, small-scale farmers often rely on watering cans or buckets to apply water directly to crops (Jiménez et al., 2023). While this approach requires minimal investment and is accessible in low-resource settings, it is labour-intensive, time-consuming, and offers limited control over water distribution.

In contrast to surface irrigation, drip irrigation is a more advanced method that delivers water directly to the plant root zone through a network of pipes and emitters, where small openings control the amount of water released to each plant without wetting aboveground plant surfaces(World Health Organization, 2006b). This minimizes water losses and improves water-use efficiency and crop productivity (Sable et al., 2019). However, drip irrigation systems require higher initial investment and maintenance, and may be susceptible to clogging and physical damage (Isikwue et al., 2016; Sable et al., 2019). In many systems, water is first stored in a tank or reservoir and then distributed through the irrigation network (Patle, 2024). The required pressure can be generated either by pumps or by gravity, where an elevated tank creates a hydraulic head that drives the flow of water through the pipes and emitters.

The water requirements of crops primarily depend on environmental conditions such as climate and soil characteristics (Ali et al., 2021). Where different crops have different water use requirements, even under the same environmental conditions, due to variations in plant characteristics and growth patterns. Crop water demand also varies throughout the growing season, typically increasing during periods of active growth.

2.3.1 Irrigation with greywater

During irrigation with untreated or treated greywater, potential risks may arise for crops, soil, and the surrounding environment (Food and Agriculture Organization of the United Nations, 2003). Furthermore, the human exposure to greywater must be considered from a health risk perspective and these issues are discussed in more detail in subsection 2.3.2.

Potential impacts on soil include reduced yield, productivity, and fertility (Food and Agriculture Organization of the United Nations, 2003). To ensure sustainable and profitable agricultural production, it is essential to maintain the long-term stability of the physical and chemical properties of the soil. However, irrigation with greywater can lead to several soil-related issues, such as accumulation of nutrients and toxic elements, increased alkalinity, reduced soil permeability, and salinization. In particular, pH values outside the normal range for irrigation (6.5–8.4) may indicate chemical imbalance in the water and can affect nutrient availability, soil structure, and plant growth (Shui Lee, 2012).

In addition, greywater may contain elevated concentrations of dissolved salts, which can accumulate in the root zone over time and further reduce soil quality and crop productivity (Grattan, n.d.). The surrounding environment can also be negatively affected, including the introduction of chemicals into ecosystems, the spread of pathogens, eutrophication of nearby water bodies, and potential health risks for animals (Food and Agriculture Organization of the United Nations, 2003).

At the same time, the reuse of greywater for irrigation presents several potential benefits (Food and Agriculture Organization of the United Nations, 2003). It can reduce pressure on freshwater resources, provide a reliable alternative water source in water-scarce regions, and contribute to nutrient recycling, potentially reducing the need for synthetic fertilizers.

To mitigate the risks associated with wastewater reuse in irrigation, appropriate control measures are required (Food and Agriculture Organization of the United Nations, 2003). Effective management includes a combination of approaches, regular monitoring of water quality, proper operation and maintenance of treatment systems as well as implementation of guidelines.

2.3.2 Human health risks

The reuse of greywater and wastewater in agriculture may pose several health risks due to the presence of pathogenic microorganisms originating from human activities and faecal contamination (World Health Organization, 2006b). The primary health hazards associated with wastewater reuse are microbiological hazards, including bacteria, viruses, protozoa, and helminths capable of causing infectious diseases in humans. Health risks arise when individuals are exposed to these pathogens through contaminated water, soil, crops, or surfaces (Food and Agriculture Organization of the United Nations, 2003; World Health Organization, 2006b).

Although treated greywater generally contains lower pathogen concentrations than untreated greywater, microbial contamination may still remain after treatment (World Health Organization, 2006a). A major source of contamination is the introduction of faecal material and associated microorganisms into the greywater stream through activities such as showering, washing faecally contaminated clothing or diapers, and childcare practices. In addition, pathogenic bacteria including *Salmonella* and *Campylobacter* may be introduced into greywater through inadequate food handling and contaminated kitchen activities.

The survival of pathogens in the environment depends on several environmental conditions and may either increase or decrease over time depending on the surrounding circumstances (World Health Organization, 2006b). Factors influencing pathogen survival include temperature, moisture content, time, exposure to sunlight, and ultraviolet radiation. Proper treatment of greywater is one of the most important measures for reducing the risks associated with pathogenic contamination. However, in many low-income settings, advanced treatment systems may not always be feasible due to technical or economic limitations. In such contexts, additional health protection measures become particularly important. Examples of such measures include washing vegetables with clean water before consumption, cooking or boiling crops prior to eating, and introducing withholding periods between irrigation and harvest to allow for natural pathogen die-off.

It is also important to consider that the health risks associated with wastewater irrigation are not limited to consumers alone (Food and Agriculture Organization of the United Nations, 2003). Farmers, their families, and nearby communities may also be exposed to pathogens through direct contact with contaminated water, soil, crops, or irrigation equipment. Individuals involved in handling, transporting, or packaging irrigated crops may similarly be exposed if appropriate precautions are not taken. Therefore, awareness of the potential risks related to wastewater irrigation and crop handling is essential for all exposed groups. The use of protective clothing and shoes, together with good personal hygiene practices, can significantly reduce the risk of pathogen transmission (World Health Organization, 2006b).

Some common health outcomes associated with improper handling of greywater during crop irrigation are related to exposure to microbial contaminants present in the water (Budeli & Sibali, 2025). These contaminants may cause waterborne diseases linked to pathogens such as *E. coli*, *Salmonella*, *Campylobacter*, and *Enterococcus*, which can result in skin infections, gastrointestinal illnesses, and respiratory infections. Viral infections caused by pathogens such as Rotavirus, Norovirus, Hepatitis A, and Adenovirus are also commonly associated with contaminated water exposure. In addition, greywater exposure may lead to parasitic infections caused by organisms such as *Cryptosporidium* and *Giardia*, potentially resulting in symptoms including diarrhoea, nausea, and abdominal cramps. Helminthic parasites may further contribute to anaemia, malnutrition, intestinal infections, and impaired physical or cognitive development, particularly among children.

The chemical composition of greywater may also contribute to long-term health risks depending on the types and concentrations of contaminants present (Budeli & Sibali, 2025). Potential health effects associated with chemical exposure include kidney damage, carcinogenic effects, reproductive disorders, and liver damage. Across most categories of contaminants, infants and children are considered the most vulnerable population groups. Pregnant women, elderly individuals, immunocompromised persons, and people with underlying health conditions are also particularly sensitive to exposure-related health risks.

2.3.3 Guidelines

Guidelines are used to ensure the safe use of wastewater in irrigation by limiting potential risks to human health (World Health Organization, 2006b). The level of required treatment and water quality depends on the degree of human exposure associated with different irrigation practices. Wastewater irrigation is commonly categorized into restricted and unrestricted irrigation. Restricted irrigation refers to the use of wastewater in situations where human exposure is limited, for example when irrigating crops that are not consumed raw or are subject to processing (Drechsel et al., 2010). In contrast, unrestricted irrigation involves the use of wastewater for crops that may be consumed raw, resulting in a higher potential for human exposure and therefore stricter safety requirements.

According to the World Health Organization (WHO) Guidelines for the Safe Use of Wastewater, Excreta and Greywater, the microbiological quality of irrigation water is mainly controlled using *E. coli* as an indicator organism (World Health Organization, 2006b). For unrestricted irrigation of crops eaten raw, the WHO guidelines recommend an *E. coli* concentration of $\leq 10^3$ CFU/100 ml, although this may be relaxed to $\leq 10^4$ CFU/100 ml for high-growing leaf crops or when drip irrigation is used (Table 2.5).

In addition to *E. coli*, the WHO guidelines also include helminth eggs as an important health-related parameter, particularly due to their persistence in the environment and their potential to cause infections in humans (World Health Organization, 2006b). For unrestricted irrigation, WHO recommends a guideline value of ≤ 1 helminth egg per litre (Table 2.5).

In Tanzania, water supply and sanitation systems are directed by national policies and technical design manuals developed by the Ministry of Water (Ministry of Water, 2020). The Design, Construction Supervision, Operation and Maintenance (DCOM) manual provides guidance for the planning, design and implementation of sanitation and wastewater treatment systems in the nation. The manual forms part of the national framework supporting water supply and sanitation services and refers to national legislation and international standards used within the sector.

Although national policies and technical manuals provide guidance for sanitation systems and wastewater treatment technologies, specific water quality guideline values for irrigation using treated greywater are not clearly defined within the national framework (Ministry of Water, 2020). Consequently, international guidelines, such as those developed by WHO, are often used as reference values when assessing the safety of wastewater or greywater reuse for irrigation purposes.

Guidelines from the United States Environmental Protection Agency (USEPA) are also frequently applied internationally in the context of water reuse, particularly for high-quality treated wastewater (U.S. Environmental Protection Agency, 2012). The USEPA guidelines suggest water quality criteria for reclaimed wastewater used for irrigation of food crops eaten raw. For pH the recommended range is 6–9, which is the same as suggested by Jordanian standards for reclaimed greywater for unrestricted irrigation (Table 2.5) (Abunaser & Abdelhay, 2020).

For turbidity, USEPA recommends levels below 2 NTU for irrigation of food crops eaten raw (U.S. Environmental Protection Agency, 2012). However, these recommendations are developed for centralized, high-level treatment systems in the U.S. and may therefore be overly stringent for decentralized greywater reuse systems in low-resource settings. In comparison, Jordanian standards for unrestricted irrigation using reclaimed greywater allow turbidity levels up to 25 FNU (Table 2.5), which is considerably higher than the value recommended by USEPA (Abunaser & Abdelhay, 2020).

In addition to the previously discussed water quality parameters, nutrient concentrations such as nitrogen and phosphorus are also important considerations when evaluating treated greywater for irrigation reuse (Food and Agriculture Organization of the United Nations, 2003). While these nutrients may contribute positively to crop growth, excessive concentrations can lead to nutrient accumulation in soils and potential environmental impacts. Jordanian standards for reclaimed greywater used in unrestricted irrigation also include guideline values for nutrient concentrations, permitting total nitrogen and total phosphorus concentrations up to 45 mg/L and 15 mg/L, respectively (Table 2.5) (Abunaser & Abdelhay, 2020).

Guideline values for organic matter also vary depending on the intended reuse application (Food and Agriculture Organization of the United Nations, 2003). According to U.S. Environmental Protection Agency, 2012, BOD_5 concentrations should not exceed 10 mg/L for irrigation of food crops eaten raw. In contrast, the Egyptian Code allows BOD_5 concentrations up to 30 mg/L for irrigation of grain crops and vegetables intended for cooking or processing, while the use of treated wastewater for vegetables consumed raw is prohibited (Ghaly, Mahmoud, et al., 2021). Jordanian standards for reclaimed greywater used in unrestricted irrigation permit substantially higher BOD_5 concentrations of up to 300 mg/L (Table 2.5) (Abunaser & Abdelhay, 2020). For chemical oxygen demand (COD), Jordanian standards for reclaimed greywater used in unrestricted irrigation permit concentrations up to 500 mg/L (Table 2.5) (Abunaser & Abdelhay, 2020).

Similar recommendations are reported for total suspended solids (TSS). Both USEPA and the Egyptian Code recommend TSS concentrations below 30 mg/L under comparable reuse conditions (Table 2.5) (Ghaly, Mahmoud, et al., 2021; U.S. Environmental Protection Agency, 2012). In comparison, Jordanian standards for reclaimed greywater used in unrestricted irrigation allow substantially higher TSS concentrations of up to 200 mg/L (Abunaser & Abdelhay, 2020).

As discussed throughout this section, guideline values for treated wastewater reuse vary depending on the intended reuse application, level of human exposure, and regulatory framework applied. Table 2.5 summarizes selected guideline values and water quality criteria relevant for irrigation reuse of treated greywater.

In addition to guideline values based on fixed concentration limits, irrigation water quality can also be assessed using classification systems based on potential risks to soil and crops (Food and Agriculture Organization of the United Nations, 2003). The Food and Agriculture Organization (FAO) provides such a framework, where water quality is evaluated according to degrees of restriction rather than strict threshold values. Table 2.6 presents a simplified compilation of the most relevant FAO parameters for this study. The FAO guidelines classify irrigation water into categories of no restriction, slight to moderate restriction, and severe restriction based on parameters such as salinity (electrical conductivity), infiltration characteristics, and specific ion toxicity. This approach reflects the fact that water quality suitability for irrigation depends not only on concentration levels but also on local conditions such as soil type, crop sensitivity, and irrigation practices.

Table 2.5: Compilation of selected guideline values and water quality criteria for treated greywater reuse in irrigation

Parameter	Range	Unit	Conditions	Source
E. coli[a]	$\leq 10^3$	CFU/100 mL	Unrestricted irrigation	(World Health Organization, 2006c)
E. coli[a]	$\leq 10^4$	CFU/100 mL	Unrestricted irrigation with drip irrigation or high-growing crops	(World Health Organization, 2006c)
Helminth eggs[a]	≤ 1	eggs/L	Unrestricted irrigation	(World Health Organization, 2006c)
pH[a]	6–9	–	Food crops eaten raw	(U.S. Environmental Protection Agency, 2012)
pH[b]	6–9	–	Unrestricted irrigation	(Abunaser & Abdelhay, 2020)
Turbidity[a]	≤ 2	NTU	Food crops eaten raw	(U.S. Environmental Protection Agency, 2012)
Turbidity[b]	≤ 25	FNU	Unrestricted irrigation	(Abunaser & Abdelhay, 2020)
Total nitrogen[b]	≤ 45	mg/L	Unrestricted irrigation	(Abunaser & Abdelhay, 2020)
Total phosphorus[b]	≤ 15	mg/L	Unrestricted irrigation	(Abunaser & Abdelhay, 2020)
BOD_5[a]	≤ 10	mg/L	Food crops eaten raw	(U.S. Environmental Protection Agency, 2012)
BOD_5[b]	≤ 30	mg/L	Grain crops, vegetables used cooked and processed	(Ghaly, Mahmoud, et al., 2021)
BOD_5[b]	≤ 300	mg/L	Unrestricted irrigation	(Abunaser & Abdelhay, 2020)
COD[b]	≤ 500	mg/L	Unrestricted irrigation	(Abunaser & Abdelhay, 2020)
TSS[a]	≤ 30	mg/L	Processed or non-food crops	(U.S. Environmental Protection Agency, 2012)
TSS[b]	≤ 30	mg/L	Grain crops, vegetables used cooked and processed	(Ghaly, Mahmoud, et al., 2021)
TSS[b]	≤ 200	mg/L	Unrestricted irrigation	(Abunaser & Abdelhay, 2020)

[a] Guideline values and water quality criteria from selected standards, guidelines and reference documents.
[b] Guideline values reported in the literature for specific national or regional reuse conditions.

Within the FAO framework, the restriction levels indicate the degree of management required to safely use the water for irrigation rather than defining strict acceptable or unacceptable limits (Food and Agriculture Organization of the United Nations, 2003). Water classified as having no restriction can generally be used without significant management concerns, whereas slight to moderate restriction indicates that certain precautions may be necessary, such as the use of salt-tolerant crops, improved drainage, or careful irrigation management. Severe restriction reflects a high potential risk of soil degradation, salinity problems, or crop toxicity, meaning that the water is only suitable under limited conditions and with intensive management practices.

Table 2.6: FAO classification of irrigation water quality based on restriction levels (Food and Agriculture Organization of the United Nations, 2003)

Parameter	Range	Unit	Restriction level
EC	< 700	μS/cm	No restriction
EC	700–3000	μS/cm	Slight to moderate restriction
EC	> 3000	μS/cm	Severe restriction
TDS	< 450	mg/L	No restriction
TDS	450–2000	mg/L	Slight to moderate restriction
TDS	> 2000	mg/L	Severe restriction
pH	6.5–8.4	–	Normal range

2.4 Social acceptance

Greywater reuse is a concept that is not well-known in all parts of the world (Food and Agriculture Organization of the United Nations, 2003). Lack of information, fear of health risks and public perception of reuse are factors that affect the reuse potential of greywater. Additionally, age, gender and education level have also been reported to influence the acceptance level (Al-Khatib et al., 2022). Furthermore, the success of a greywater treatment system is highly dependent on public awareness and acceptance (Jamrah et al., 2006).

By investigating social acceptance prior to implementation, it is possible to raise public awareness of the concept, which will influence the feasibility of the treatment system (Jamrah et al., 2006). Several studies have conducted social acceptance surveys in order to address this issue (Al-Khatib et al., 2022; Jamrah et al., 2006). The surveys included questions regarding respondent characteristics, perceptions of greywater reuse, and influencing factors.

Generally, greywater reuse without direct human contact like construction, bush- and crop irrigation, is more accepted compared to toilet flushing and drinking (Al-Khatib et al., 2022). Public education is suggested to be the most important factor to increase the acceptance. Among people who do not accept greywater reuse, their strongest concerns are related to health risks, economic factors and environmental impacts (Jamrah et al., 2006).

To increase social acceptance, training on how to use the reuse system must be included as part of the implementation (Food and Agriculture Organization of the United Nations, 2003). Through training, it is possible to reduce the health and environmental risks related to reuse. Furthermore, a management framework should be established before operation of the system in order to supervise and control the treatment process, while also clarifying responsibilities related to operation and maintenance.

3 Case study description

Tanzania is located in East Africa, covering an area almost twice the size of Sweden and having a population of approximately 69 million inhabitants (Globalis, 2025; World Bank Group, n.d., 2009). The country hosts both Africa's highest mountain, Mount Kilimanjaro, and parts of its largest lake, Lake Victoria (World Bank Group, 2009). These physical features contribute to diverse climate zones across the country (Magang, 2025). Almost 50% of Tanzania's land area is used for crop production, which is strongly dependent on precipitation. Historical trends indicate declining precipitation of -45.9 mm/decade and rising temperatures of +0.2 °C/decade in Tanzania. Rain patterns are influenced by both global weather oscillations and local environment affecting the microclimate. Weather oscillations such as El Niño and La Niña have been shown to influence precipitation patterns, temperature variability, and the intensity of wet and dry period. Climate change enhances the effects of natural oscillations, thereby intensifying extreme weather. Consequently, Tanzania is expected to suffer from increased drought occurrence, duration and frequency (Haile et al., 2020; Magang, 2025). Furthermore, these changes are expected to affect agriculture, food security and the country's economy (Magang, 2025).

The case study area, Tumaini Open School, is located in rural Tanzania, approximately 15 km south of the city of Tabora, in Isukamahela village (see Figure 3.1).

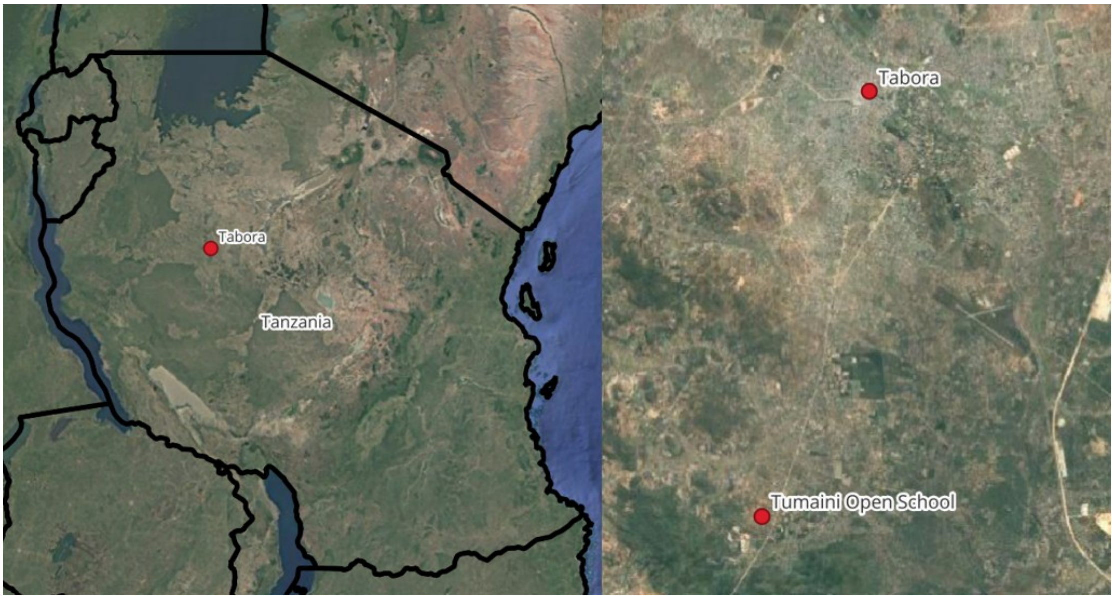


Figure 3.1: Map showing the location of Tabora in Tanzania (left) and the study area Tumaini Open School in relation to Tabora (right).

Climatically, the region experiences both a wet season (mid October – April) and a dry season (May – October) during the year. The annual precipitation in Tabora is approximately 1093.2 mm, with most of the rainfall occurring during the wet months from October to April (**timeanddateClimateTanzania**). In addition to rainfall amounts, the average number of rainy days per month provides further insight into the seasonal distribution and frequency of rainfall events throughout the year. As presented in Table 3.1, the number of rainy days varies considerably between seasons, ranging from an average of 0.1 rainy days in July to 19.7 rainy days in December (Weather Spark, n.d.).

Wet season	Days of rain	Dry season	Days of rain
October	3.5	May	3.0
November	11.6	June	0.2
December	19.7	July	0.1
January	19.5	August	0.2
February	16.3	September	0.6
March	17.5		
April	11.6		
Total wet season	**99.7**	**Total dry season**	**4.1**
Total rainy days per year: 103.8			

Table 3.1: Average number of rainy days per month in Tabora divided into wet and dry season (2018–2026) (Weather Spark, n.d.).

In 2022, Tabora Region had a population of approximately 3.4 million, with about 85% of the population residing in rural areas (The United Republic of Tanzania, 2024). The population has grown steadily, increasing by approximately 3.9% between 2012 and 2022. The region is characterised by a low median age and a high proportion of young people. Livelihoods are predominantly based on agriculture, forestry, and fishing, which account for the majority of employment in the region.

In 2022, approximately 41.9% of households in Tabora Region relied on improved sources of drinking water, while the remainder depended on unimproved sources such as unprotected wells and surface water (The United Republic of Tanzania, 2024). Similarly, only about 33.8% of households had access to improved sanitation facilities. Solid waste management is also constrained, with nearly 38.9% of households relying on burning as the primary method of waste disposal.

3.1 Tumaini Open School

Until 2021, adolescent mothers in Tanzania were banned from continuing their education. Although this policy has changed, social stigma persists in many parts of society, where teenage pregnancies are often viewed negatively. According to World Bank estimates from 2021, approximately 6,500 girls drop out of school each year in Tanzania due to pregnancy (World Bank, 2021).

Tumaini Open School is an inclusive learning centre that provides a second chance for education to young mothers and girls from vulnerable backgrounds. The school offers both basic education and vocational skills training (Tumaini Open School, n.d.). Enrolment is open to young mothers and other vulnerable girls who have been unable to continue formal schooling due to challenges such as stigma, poverty, or other social barriers. The school offers accommodation for all students, which enables them to continue their education and work towards long-term independence. The education is structured into two stages. Stage 1 corresponds to the first two years of the conventional secondary education system, while Stage 2 corresponds to the final two years. At Tumaini, each stage is completed in one year, meaning that students complete the equivalent of four years of secondary education in a two-year period. In addition to formal education, the school provides guidance and counselling aimed at strengthening students' self-esteem and self-confidence. Furthermore, students participate in a range of extracurricular activities, including sports and games, gardening, poetry classes, and creative practices such as music, while additional activities such as sewing are planned for future implementation.

The school collaborates with Engineers Without Borders Sweden (EWB-SWE) in initiatives aimed at supporting the continued development of the school and exploring opportunities for increased resource self-sufficiency (**EngineersWithoutBordersApplySWE**). Currently, as of March 2026, the school hosts 84 students and provides full-time accommodation for five teachers, while an additional five staff members are present during daytime. In the long term, the school aims to accommodate up to 450 students.

Figure 3.2 illustrates the current land use within the school boundaries, including existing buildings, areas under development, and key functional zones such as agricultural land, water infrastructure, and sanitation facilities. In 2021, the southern part of the school, including three classrooms, was constructed. The following year, the toilet building located north of the school was built, consisting of four squatting toilets and two sinks with running water. Dormitory 1 also began to be constructed and was completed in 2022. A land use plan was developed by EWB-SWE in 2022. However, ongoing development and the construction of new buildings have resulted in deviations from the initial plan.

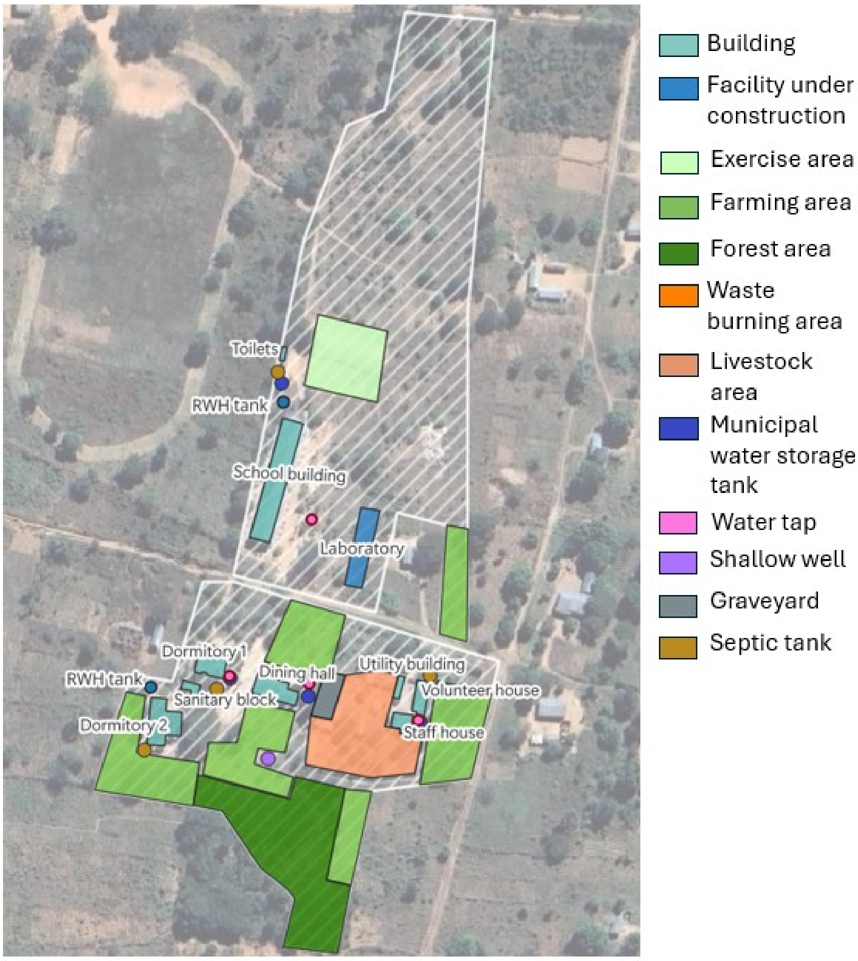


Figure 3.2: Current situation plan of Tumaini Open School (March 2026)

In 2023, additional land was purchased on the southern side of the campus, expanding the school area with extra farmland and a forested area. The acquired land also included a potential site for a borehole. However, excavation revealed no accessible groundwater. It was therefore concluded that the borehole would not provide a meaningful water source within the school premises.

The school opened in 2024, and additional construction has since been carried out in a stepwise manner. During the same year, the sanitary block for the students was built, including eight washrooms and four squatting toilets. Currently, no running water is connected to the building. Furthermore, the dining hall was constructed, which provides seating for 68 students with 18 tables. Prior to its construction, students dined outside. As the school continues to develop and enrol more students, a new dining hall will be constructed according to the land use plan. Consequently, the purpose of the current dining hall may change depending on the future needs of the school.

Between 2024 and 2025, the staff house was constructed. It includes a small kitchen, staff accommodation, one squatting toilet, and one washroom. In addition, a separate building for volunteers, with three bedrooms and attached bathrooms equipped with a hand basin, shower, and a flush toilet was built. At the same time, the northern part of the school building was completed, adding two additional classrooms and a teachers' office. One of the classrooms is currently used as a laboratory.

In 2025, Dormitory 2 was completed, enabling more students to be enrolled at the school. At present, not all rooms are occupied, and an additional five squatting toilets and six washrooms are being constructed. A separate living space for a teacher is also being added to Dormitory 2, consisting of a bedroom, living room, and a private bathroom with a squatting toilet. This will allow a teacher to stay closer to the students after school hours.

Currently, as of March 2026, Tumaini Open School is constructing two rainwater harvesting (RWH) tanks, as seen in Figure 3.2, with a diameter of 5 m and a height of 6 m. Furthermore, a laboratory building is being constructed (see location in Figure 3.2), and once completed, the classroom currently used as a laboratory in the main school building will be converted back into a regular classroom. A feasibility study conducted by Engineers Without Borders is also exploring the possibility of installing an additional water tank near the school laboratory.

In addition to the ongoing construction, the school has several future development plans aimed at expanding its capacity and improving infrastructure. Planned developments include additional dormitories, with future units designed to accommodate up to 100 students each. Administrative facilities and a library are also part of the long-term plan. These developments are expected to be implemented progressively over an approximate five-year period.

Improvements in water-related infrastructure are also planned. This includes a centralized laundry station located in the dormitory area and designed for student use. The facility is expected to accommodate approximately 30 students simultaneously and will provide access to washing at an appropriate working height with running water. In addition, the centralized setup will enable more efficient collection of greywater for potential treatment and reuse.

3.1.1 Water infrastructure and management

The school faces water scarcity during most parts of the year. Currently, the school relies on two main water sources. The primary water source is the municipal water supply, conveyed through pipelines from Lake Victoria, located approximately 250 km away. The water enters the school through a pipe located beneath one of the roads passing through the campus. The supply is however highly unreliable and can abruptly stop functioning. Interruptions are caused by failures at pumping stations, technical issues along the pipeline, or the municipality's failure to pay the bills. The municipal water is advised to boil before consumption, however, boiling is not currently practised at the school. To buffer outages, four 5,000-L above-ground plastic tanks on concrete stands store municipal water for daily use (see locations in Figure 3.3), though they are insufficient for prolonged shutdowns. Through the tanks, water is dispatched to access points marked with a pink dot in Figure 3.3. Furthermore, some buildings such as the volunteers house, the staff kitchen and the toilets are also connected to water. However the main access points are most frequently used to get water for drinking, cooking, washing dishes, and laundry.

Figure 3.3: Water infrastructure at Tumaini Open School (March 2026)

The consumption of municipal water is recorded separately for three different areas of the school, as shown in Figure 3.3. The consumption of municipal water is recorded separately for three different areas of the school, as shown in Figure 3.3. Monthly invoices provide the total water consumption for each area, average monthly consumption for the dry and wet seasons of 2025, as well as for January–February 2026 are presented in Table 3.2. However, it should be noted that water use is not strictly confined to the area from which it is supplied. For instance, students often collect water from the tap in Area II and transport it for use in Area I, such as for irrigation, washing, or showering. This inter-area transfer introduces some uncertainty in attributing water consumption to specific uses within each area. Additionally, in Area II, the construction of the laboratory and the rainwater harvesting tank required substantial amounts of water. Consequently, the water invoices from 2025 are not strictly correlated with domestic water use, such as drinking water and toilet flushing.

Table 3.2: Average monthly water consumption for each area based on seasonal conditions.

Season	Area I	Area II	Area III	Total
Dry season (May–Sep 2025)	73 200	39 000	15 000	127 200
Wet season (Oct–Apr 2025)	57 900	37 860	23 000	118 714
Jan–Feb 2026	43 000	18 000	24 000	85 000

The second water source is a 12 m shallow well, with 1 m in diameter, see purple dot in Figure 3.3. When the municipal supply is operational, the well is primarily used for irrigation of the agricultural areas. Water is typically collected manually using a bucket attached to a rope. The well has an estimated yield of around 1000 L per day which can be used to irrigate approximately 500 m^2. During periods of municipal water outages, it is also used as a source of potable water and is considered safe for drinking. However, due to its limited yield, it cannot meet the school's water demand for extended periods.

On average, water outages occur approximately 10 days per month. During the wet season, interruptions are more frequent but shorter, lasting around two days at a time. In contrast, water scarcity is significant during the dry season, when outages can last up to 14 consecutive days.

The primary water uses at the school include drinking, sanitation, and cooking. Additional water demands, such as irrigation for agricultural activities and water use for construction, represent secondary uses and are dependent on the availability of water resources.

All toilet facilities at the school are connected to septic tanks, with a total of five tanks located on the premises. The tanks vary in size and are emptied when full, either by private contractors or municipal services using vacuum trucks. In the volunteers' house, the septic tank also receives wastewater from the hand basin and floor drainage, in addition to toilet wastewater. In contrast, greywater generated from laundry, showers, and dishwashing in other parts of the school is discharged untreated into the surrounding environment, either via pipe outlets or through direct disposal from buckets. Apart from the septic systems, no wastewater treatment is currently implemented on site.

3.1.2 Agricultural practices

The agricultural practices at the school vary depending on the season. During the dry season, crop production is more limited compared to the wet season. Figure 3.4 shows both the current and the planned future areas used for farming. The numbered farming areas 2–5 in Figure 3.4 are currently in use during the wet season, and consist of a total area of 3037 m^2. In the future, the total cultivated area is planned to increase to 4522 m^2 (see Table 3.3). Farming area 3 also includes a small-scale propagation area where seeds and cuttings are grown in a shaded environment before being transplanted into the fields. Farming area 1 and 6 are currently not in use and are either left uncultivated

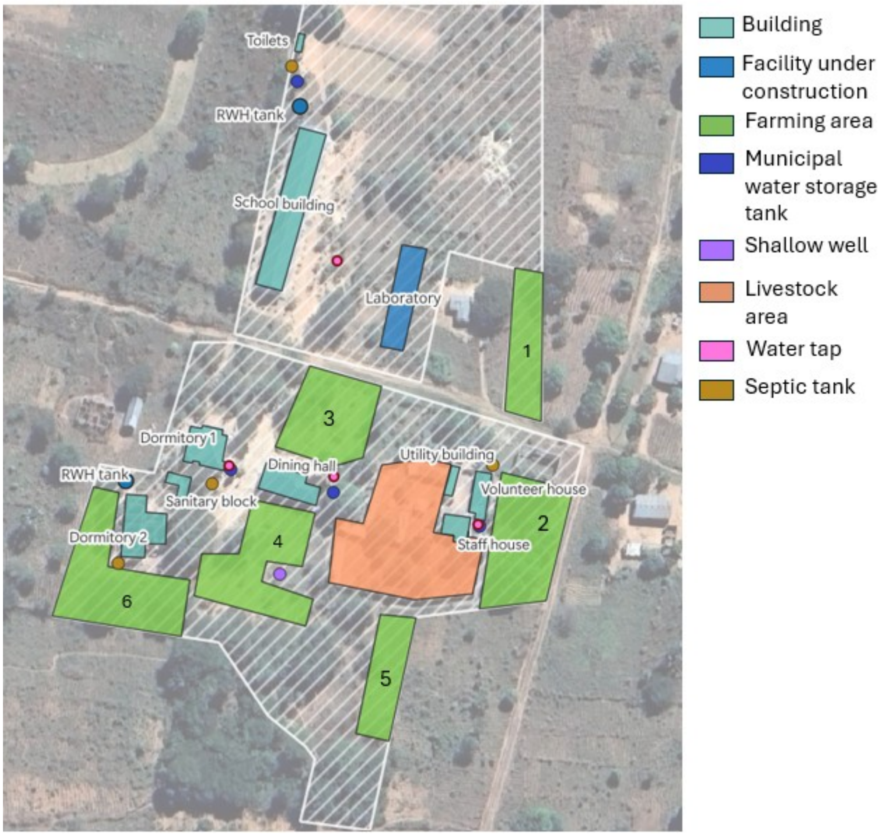


Figure 3.4: Present and future farming lands numbered 1-6 at Tumaini Open School (March 2026)

or made available for temporary use by neighbouring farmers. This is mainly due to financial constraints and limited available time, as both students and teachers are primarily occupied with school activities. In addition, the lack of a reliable water source further restricts the use of these areas for cultivation. In the future, the school aims to expand agricultural activities by employing dedicated staff to manage the farming areas, provided that sufficient funding becomes available.

Farming land	Area (m^2)	Current crops
1	450	Not in use
2	930	Corn
3	750	Tomatoes, onions, beans, watermelon, corn and pumpkin
4	897	Pumpkin, watermelon
5	460	Corn
6	1035	Not in use

Table 3.3: Overview of farming areas at Tumaini Open School

During the dry season, crop production is lower compared to the rainy season. Only farming area 3 and parts of area 4 around the well are cultivated, with an approximate area of 1500 m^2. As a result, the school has a higher consumption of purchased food. Most vegetables can still be cultivated, although production is more limited. Irrigation is required daily, and during particularly dry periods or for certain crops, irrigation may be needed twice per day. For example, potato leaves require relatively little water, whereas Chinese cabbage requires more water and must be irrigated daily. The students are mainly responsible for irrigating the crops. Irrigation is currently carried out manually using buckets, where around 0.5–1 L water is required per plant.

Soil fertility is maintained through a combination of organic and inorganic inputs. Manure from the school's farm is collected and applied to the fields, while industrial fertilizers are also purchased and used to supplement nutrient supply when needed.

During the rainy season, crop cultivation becomes easier as irrigation is generally not required due to the frequent rainfall. However, if several consecutive days pass without rainfall, manual irrigation is required. Crops such as maize require large areas and significant amounts of water and are therefore mainly produced during the rainy season. Other crops grown at the school include sweet potatoes, potatoes, cassava, okra, and beans. In general, most crops can be cultivated during the rainy season. However, challenges remain, particularly insect attacks, which are especially problematic for crops such as watermelons and tomatoes. Pesticides could be used to address these issues, however, the school refrains from using them in order to maintain organic production practices.

In addition to crop production, the school also operates a small-scale farm that includes a range of animals. The livestock area is located next to the staff house, as shown in Figure 3.4, and covers an area of approximately 1510 m^2. The livestock includes around 300 chickens and roosters, 12 turkeys, 5 ducks, 6 rabbits, 8 guinea fowl, and 3 pigs.

The animals are primarily kept for food production, providing meat for the school, while chickens also contribute through egg production. Together, crop production and livestock form an integrated farming system that supports food production at the school.

3.1.3 Waste management

Three waste burning spots are located across the school premises as seen in orange in Figure 3.2. Waste generated at the school is first collected in smaller bins distributed around the area. The waste is then transported to the waste burning spots, where it accumulates and is burned once the burning area becomes full. Plastic water bottles are collected and either cleaned and reused by students or sold for recycling. Glass containers from soda are also recycled and returned to the seller before new bottles are purchased. Metal scrap is collected, sold and then recycled. However, all other waste is burned in the designated areas. In addition, organic waste in the form of animal manure is generated from the school's farm area. This material is collected and stored in piles, where it is later reused as fertilizer for the school's agricultural activities.

4 Methods

The study involved several steps, including a literature review, field studies at the case study site, and the development of a greywater treatment and reuse solution. The following sections describe the methods used in the project.

4.1 Literature review

A literature review was conducted throughout the study, with the main focus during the initial phase, in order to gather and evaluate relevant research within the scope of the project. The search engine Google Scholar was primarily used to identify academic sources, as it facilitates access to peer-reviewed and highly cited publications. Search strings were constructed using combinations of keywords such as *"greywater"*, *"rural"*, *"decentralized"*, *"irrigation"*, *"QMRA"* and *"water treatment"*. These keywords were selected to reflect the technical and contextual aspects of the study, enabling a broad yet relevant literature base. The search terms were combined using Boolean operators (e.g. AND, OR) to refine and broaden the search results.

The literature review process was iterative, meaning that previously identified sources were continuously revisited and used to explore new topics as the study progressed. In addition to database searches, a snowballing approach was applied, where references cited within relevant publications were used to identify further sources. Throughout the literature review, efforts were made to identify and consult original sources whenever possible, in order to ensure accuracy and reliability.

Peer-reviewed journal articles formed the primary basis of the literature review, due to their scientific rigour and credibility. However, these were complemented by selected grey literature, such as reports and publications from organizations. While grey literature can provide valuable context-specific information, it was used with caution due to the lack of formal peer review and potential variability in quality.

Relevant references were managed using Mendeley, a reference management tool used to organize academic sources. Important information was highlighted, and notes and comments were added to facilitate analysis and writing. The software also enabled efficient citation management and collaboration between authors.

Specific contextual information regarding the region of Tabora and Tumaini Open School was obtained through communication with the headmaster, the school coordinator, as well as other staff members and students. This information was used to complement the literature and provide a more comprehensive understanding of local conditions.

4.2 Field assessment

Field assessments were conducted at Tumaini Open School and its surrounding area to collect primary data and gain an understanding of site-specific conditions. The assessment focused on spatial layout, water generation and use, as well as social practices related to water handling.

An initial walk-through of the school premises was carried out to obtain an overall understanding of the site. During this process, observations were made regarding daily routines, spatial movement patterns, and locations where greywater was generated. Particular attention was given to identifying greywater sources, focusing specifically on showers, laundry activities, kitchen facilities, and handwashing stations.

The site was documented through photographs, field notes, and GPS coordinates, which were later used to develop a series of site maps illustrating greywater sources, spatial layout, and other relevant site characteristics.

To complement the site observations, additional data on water use and greywater generation were collected through questionnaires, informal interviews with students and staff, and direct measurements at selected water sources. These methods were used to obtain both qualitative and quantitative information regarding water use patterns and volumes. Further details on the data collection and processing methods are presented in Section 4.3.

4.3 Determination of volumes and distributions

Spatial and temporal patterns of greywater generation were assessed using two questionnaires, an observation checklist and by manually measuring volumes. The aim was to obtain an understanding of when greywater is produced during a typical day and week, as well as which facilities contribute to the greywater flows. The questionnaires focused on water use habits related to laundry, handwashing, kitchen activities and showering.

The first questionnaire was given to 30 students, and the results were assumed to be representative of the entire student population. The second survey was administered to 4 of the 5 teachers living at the school, and the data were extrapolated to assume similar behaviour among all teachers. The results from the questionnaires provided a general understanding of water use patterns, including the number of 10 L buckets used for each activity as well as the frequency and timing of activities throughout the day and week. The questionnaire is presented in Appendix B.1.

To complement the findings from the questionnaires, a checklist-based observation method for the handwashing station at the toilets by the school, was conducted over one full day. Students marked each time they used the handbasins in the corresponding time slot. The results from the observation checklist can be found in Appendix A, Table A.2. This provided an understanding of the temporal variation in handwashing activities.

To estimate greywater volumes from selected sources, direct measurements were conducted. For handwashing stations and kitchen activities, 25 L buckets were placed beneath the outlets for one hour at a time, after which the collected volume was measured and recorded. These measurements were used to complement the activity data obtained from the questionnaires and observation checklist. In addition, the volume of water used by students when rinsing their plates after meals was measured in order to better estimate the greywater generation from kitchen-related activities.

The collected data were compiled in an Excel spreadsheet and used to estimate greywater generation and its distribution between activities.

4.3.1 Greywater volume estimation

Initially, greywater volumes were estimated directly from the questionnaire responses, where users reported the number of buckets used for different activities. Each bucket was initially assumed to contain 10 L.

When the calculated greywater volumes were compared with total water consumption from monthly invoices, the estimated greywater generation exceeded the measured water use from the invoices (see Table A.1). Two main explanations were identified: respondents may have unintentionally overestimated their water use in the survey, and the formulation of the questionnaire may have introduced uncertainties in the reported bucket volumes. Even when adjusting the calculations to assume half-filled buckets, the estimated greywater generation remained higher than the measured total water consumption.

Therefore, an alternative method was applied using literature values for greywater generation. The questionnaire data were instead used to determine the relative distribution of water use between activities rather than absolute volumes.

For laundry (students and teachers), showers (students and teachers), and dishwashing (teachers), the total number of buckets used per week was estimated using Equation 4.1.

$$B_{week} = \bar{B}_{activity} \cdot f_{week} \tag{4.1}$$

where:

- B_{week} = total number of buckets used per week for an activity
- $\bar{B}_{activity}$ = mean number of buckets used per activity
- f_{week} = average number of times the activity occurs per week

For handwashing and kitchen activities, bucket counts could not be determined since water was supplied from taps rather than buckets. Instead, the water volume was estimated using Equation 4.2. The flow rate from each source was determined by measuring the volume collected in a 1 L container over a specified period of time. For the toilets located by the school, two water taps with different flow rates are present. The average flow rate was therefore estimated by weighting the number of users choosing each tap based on the checklist results. For students doing dishes, the water volume was estimated through direct measurements by collecting the water used during dishwashing in a bucket and recording the average volume required. Since food preparation also contributes to water use, its average volume was added to the dishwashing volume based on the direct measurements.

$$V = Q \cdot t \cdot n \cdot N \tag{4.2}$$

where:

- V = total water volume [L]
- Q = flow rate [L/s]
- t = average duration per event [s]
- n = average number of events per person per day
- N = number of users

The resulting volume was converted to an equivalent number of buckets based on the assumed bucket volume corresponding to a half full bucket. The number of buckets estimated for each activity was summed for each Area (I, II and III). The relative contribution of each activity to the greywater generation was calculated with Equation 4.3.

$$P_i = \frac{B_i}{\sum_j B_j} \tag{4.3}$$

where:

- P_i = fraction of greywater originating from activity i
- B_i = number of buckets associated with activity i
- $\sum_j B_j$ = total number of buckets from all activities in the area

This percentage was multiplied by the estimated monthly greywater generation in each area to determine the contribution of each greywater source. The greywater generation was calculated based on the monthly average water consumption in 2026, obtained from invoices for each area (Table A.1), and multiplied by a factor of 0.6. This factor represents the proportion of greywater relative to total water consumption and was derived from literature values ranging from 0.5–0.7 (Jamrah et al., 2006; Tusiime et al., 2022).

4.3.2 Temporal distribution of greywater generation

Based on the total volumes calculated for each activity and area, a temporal distribution of greywater generation was estimated using the questionnaire results as well as the observation checklist.

For each activity, a temporal distribution over the days of the week and the hours of the day was established. The probability of an activity occurring on a specific day was estimated according to Equation 4.4. These probabilities were then used as weighting factors to distribute the total weekly greywater volume across the days of the week, thereby defining the weekly profile.

$$P_{day} = \frac{n_{day}}{n_{tot}} \tag{4.4}$$

where:

- P_{day} = probability of the activity occurring on a specific day
- n_{day} = number of responses indicating the activity on that day
- n_{tot} = total number of responses for the activity during a week

Activities occurring regularly every day, such as showering, handwashing, and kitchen activities, were assumed to have an equal probability of occurring on each day of the week. Whereas the weekly temporal distribution for laundry were estimated through the questionnaire.

The daily distribution of greywater generation was determined using the same approach as described in Equation 4.4, but applied to time periods instead of days, such that the probability of an activity occurring within each period was calculated based on the corresponding number of responses. Since many students do not have access to a clock, time intervals were linked to the daily meal schedule. The day was therefore divided into five periods: before breakfast, between breakfast and lunch, between lunch and dinner, after dinner and night as seen in Table 4.1. Since meals occur at fixed times at the school, participants were able to consistently categorize the timing of their activities.

Table 4.1: Time periods used to describe the daily distribution of greywater generation.

Time period	Duration	Hours [h]
Before breakfast	06:00–10:00	4
Between breakfast and lunch	10:00–14:00	4
Between lunch and dinner	14:00–19:00	5
After dinner	19:00–23:00	4
Night	23:00–06:00	7

For laundry and showering, the temporal distribution was directly based on the survey responses. Handwashing in the dormitory was assumed to occur at a constant rate during the daytime period (06:00–22:00) based on observations of the students' behaviours. However, the daily distribution of handwashing conducted at the toilets by the school was estimated with the results from the observation checklist. For kitchen activities, the temporal distribution was determined using direct volume measurements. These measurements indicated that the flow occurred primarily during meal preparation and up to one hour after the meals due to dishwashing in the student kitchen. For Area III (teachers' area), dishwashing activities followed a different pattern. Based on observations and information given by the staff, dishwashing occurred before breakfast and between lunch and dinner rather than after each meal.

Based on this information, a weekly profile of greywater generation was developed using MATLAB. The monthly greywater generation for each source was first converted into weekly volumes in order to match the temporal distributions retrieved from the surveys. The MATLAB code for Area I is presented in A.1.

The weekly distribution was represented as a vector with seven values, corresponding to each day of the week. The daily distribution was represented as a vector with four values, corresponding to the four defined time periods during the day. Since these time periods have different durations, the number of hours in each interval was also defined in a separate vector. The night period was treated separately and assumed to have zero flow.

To obtain the weekly greywater generation profile, Equation 4.5 was applied for each day, where the daily volume was calculated from the total weekly volume using the corresponding daily probability.

$$V_{day} = V_{week} \cdot P_{day} \tag{4.5}$$

where:

- V_{week} = total weekly greywater volume [L/week]
- P_{day} = probability of the activity occurring on a specific day

The same approach was then applied at the daily level, where the daily volume was distributed across the defined time periods based on the corresponding probabilities for each interval. The volume within each time period was subsequently distributed evenly over the corresponding hours.

To obtain an hourly flow rate, the volume in each time period was divided by the number of hours in that interval. The hourly profiles for all greywater sources were then summed to obtain the total greywater generation profile for the area during a week. The resulting weekly profile was used to identify peak flows over the week and to determine the design flow for each area.

4.3.3 Sensitivity analysis

The generated greywater volumes were estimated based on literature values describing the fraction of greywater generated from total water consumption. Reported values differed substantially between different contexts, as shown in Table 2.1. In the volume calculations, a conservative value of 0.6 was used to estimate greywater generation from the reported water consumption in the area. This value was chosen to simulate a more conservative scenario and to avoid overestimating the generated greywater volumes for each area. Thus, the risk of overestimating the amount of water available for irrigation was minimized, avoiding making the proposed reuse system appear more capable than it may be under actual conditions.

Therefore, a sensitivity analysis was done using a value of 0.5 and 0.85 to test for minimum and maximum variations based on reported values. By changing the chosen greywater generation fraction in the calculations, varying volumes per Area was calculated, to identify how sensitive the results are to varying inputs.

4.3.4 Greywater generation per person

The greywater generation per person and day was obtained separately for students and staff using Equation 4.6. The number of students was set to the current 84 persons living in Area I. For the staff, however, it was stated that there are often people living in the volunteers' house. Therefore, seven persons were assumed to be living and using water in Area III.

$$q_{\text{gw}} = \frac{V_{\text{week}}}{7 \cdot n} \tag{4.6}$$

where:

- q_{gw} = Average greywater generation per person and day [L/person/d)]
- V_{week} = total weekly greywater volume [L/week]
- n = number of people contributing to the greywater generation

4.4 Water quality assessment

The water quality assessment aimed to evaluate the characteristics of different greywater sources and their suitability for treatment and reuse for irrigation. The assessment also aimed to compare the quality of greywater from different sources and to evaluate the treatment performance of the prototype as discussed in Section 4.5, by analysing water quality before and after filtration. The results were further used, in combination with literature values and existing guidelines for irrigation with treated greywater, to support the selection of suitable greywater sources and inform the design of the final system. In addition, the findings provided input to the QMRA which was used to evaluate human health risks (see Section 4.8).

Greywater samples were collected from four sources: showers, kitchen activities, handwashing stations, and laundry. Where possible, greywater was collected directly in 24 L buckets by placing them beneath outlets or drainage points. However, the feasibility of this approach varied depending on the source and local practices.

Field measurements were conducted in situ using a multiparameter portable meter from Hanna Instruments Canada to record temperature, pH, turbidity, electrical conductivity, total dissolved solids (TDS), and oxidation-reduction potential (ORP) (Hanna Instruments Canada, n.d.). The instrument was calibrated prior to use according to manufacturer guidelines, and distilled water was used to clean the probe between measurements. In addition, pH test strips (pH-Fix 0–14, Fisherbrand, Fisher Scientific no. 10642751) were occasionally used to verify the accuracy of the multimeter readings. The strips provided a colourimetric indication of pH over a range of 0–14 and were interpreted by visual comparison with a reference scale.

Nitrate concentrations were screened using MQuant nitrate test strips (catalogue number 110020, Sigma-Aldrich). The strips provided a semi-quantitative colorimetric indication of NO_3^- concentration by comparing the colour change of the test pad to a reference scale (Merck, n.d.), which was interpreted visually, and additionally supported by a mobile application associated with the test strips for digital colour analysis. These strips were selected due to their suitability for rapid field-based screening.

All measurements were documented using photographs and subsequently compiled in an Excel spreadsheet. The dataset was structured to distinguish between different greywater sources and sampling events, and included all measured parameters as well as contextual information such as time, sampling location, observed colour, and possible smells.

Due to limited laboratory availability, quantitative microbiological analysis of *E. coli* could not be carried out within the scope of the project. Instead, a limited qualitative assessment was conducted using a light microscope at a local hospital laboratory in Tabora. Selected untreated greywater samples from showers, dishwashing, and handwashing used by students, as well as laundry greywater generated by the master's thesis students, were examined under 10× magnification. In addition, one treated sample of kitchen greywater after filtration through the prototype was also analysed.

The microscope images could provide an indication of biological activity, particulate matter, and the possible presence of microorganisms. However, no quantitative analysis or reliable identification of specific microorganisms could be performed due to the low magnification of the microscope. Consequently, microbiological data from literature sources with similar conditions and comparable greywater characteristics were instead used as input for the QMRA.

Additionally, the BOD/COD ratio could not be measured using either the equipment available in situ at the school or the laboratory facilities at the hospital. Therefore, similarly to the *E. coli* concentrations, this parameter was instead estimated for the different greywater sources at the school based on values reported in literature.

4.5 Prototype

A prototype was constructed to test how locally available materials could function as filter media for greywater treatment and to evaluate their effectiveness. The prototype was used to assess the suitability of these materials for inclusion in the proposed final treatment solution. It also provided insights into user perspectives, feasibility, and how the system could be adapted to the local context.

The prototype was constructed in the middle of the fieldwork rather than at the beginning, as time was initially required to identify locally available materials and understand what solutions were feasible to implement in the local context. Building the prototype at this stage also allowed its performance to be observed over an extended period. Based on the findings from the field assessments and literature review, the design of the prototype was developed as described in the following section.

The conceptual model of the prototype can be seen in Figure 4.1. The containers used in the prototype consisted of 24 L plastic buckets with a height of 34.5 cm and a diameter of 30 cm. The buckets were purchased together with lids. Each bucket was modified with drainage holes in the lid and in the bottom of the bucket, except the empty bucket in the bottom which is used to collect the filtered greywater. The holes were created by manually puncturing the surface using a hammer and nail. The buckets were stacked vertically, allowing the greywater to flow through the system by gravity from the top bucket to the collection bucket at the bottom.

The sand was sourced from the school premises, where the roads consist of sand, and was collected using a spade. Only the uppermost dry layer of sand was collected, as it was easier to sieve and helped reduce the amount of fine particles. A sieve with an approximate mesh size of 0.8 mm was used. The dry sand was sieved, and the coarser particles retained on the sieve were saved for use in the filter. Based on ocular inspection and measurements, the grain size ranged approximately between >0.8 and 2 mm. The sand was then rinsed with clean water approximately eight times, until the rinse water appeared clear, before being spread out to air-dry in the sun on a cotton fabric.

The wood charcoal was bought from neighbours who produce it. The charcoal pieces were crushed into smaller fragments by placing them in a bag and breaking them with a hammer. The material got sieved in the same sieve as the sand to sort out the finest particles, thus leaving a grain size ranging from >0.8-20 mm. The crushed charcoal was then rinsed using the same procedure as for the sand, although six times was enough for the rinse water to be clear.

Additional materials required for the prototype consisted of a drainage gravel layer and a smaller transition layer placed between the filter media and the drainage layer. The gravel and transition gravel were purchased from a nearby quarry located approximately 2 km from the school. At the site, larger rocks are crushed manually, whereas smaller fractions are produced using machinery to achieve the desired grain sizes. The transition layer had a grain size ranging from 5–20 mm, with most particles being approximately 8 mm in diameter. The drainage gravel layer had a grain size ranging from 12–25 mm, with the majority of the particles being around 20 mm in diameter. The material was cleansed in the same way as the sand and charcoal, however, fewer washes were required due to the lower content of fine particles.

In addition, a layer of cotton fabric was placed between each filter layer to prevent mixing of materials and reduce the transport of fine particles. The fabric was cut into square pieces slightly larger than the bucket diameter and positioned on top of each layer. It was secured by placing small amounts of gravel along the edges and folding the excess fabric inward to ensure stability.

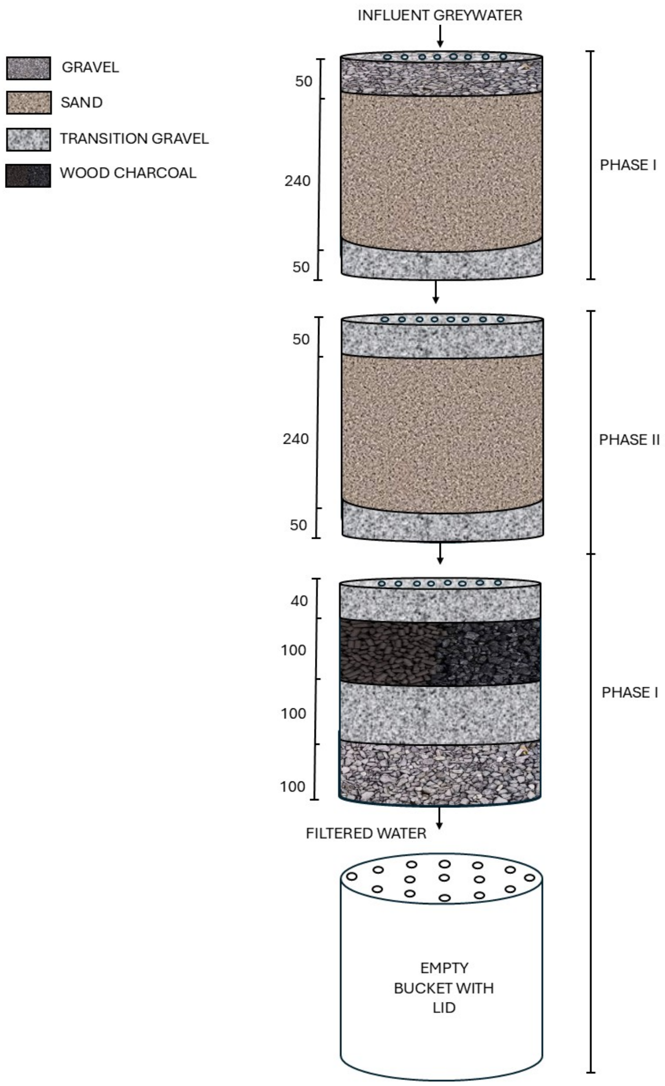


Figure 4.1: Conceptual model of the prototype, including the bucket configuration and materials.

Pore volume tests were conducted to estimate the porosity of each filter medium after sieving. The test was performed by placing a measured volume of the material into a 1 L container and gradually adding water until the medium was fully saturated. The volume of water required to saturate the medium was recorded and used to estimate the porosity according to Equation 4.7. The results are reported together with the media depth and grain size distribution in Table 4.2.

$$n = \frac{V_{water}}{V_{medium}} \tag{4.7}$$

where:

- n = porosity [-]
- V_{water} = volume of water required to saturate the media [mL]
- V_{medium} = volume of the filter media tested [mL]

The prototype was constructed in two phases as seen in Figure 4.1. Phase I consisted of an empty collection bucket, one bucket containing wood charcoal with a drainage layer, and a top bucket containing sand and gravel. A transition layer was placed at both the top and bottom of each bucket to reduce the amount of fine particles near the drainage holes, as these could otherwise clog the holes. However, after two days of testing, it was observed that the filter depth in Phase I proved insufficient treatment for effective contaminant removal. Therefore, in Phase II an additional bucket containing sand with the same filter depth as the first sand layer was added, effectively doubling the total sand depth to 480 mm in the prototype. The final configuration of the filtration system is summarized in Table 4.2.

Table 4.2: Overview of the layered filter configuration in the three-bucket system, including layer type, depth, grain size, and porosity

Bucket	Layer	Depth [mm]	Grain size [mm]	Porosity [–]
1	Gravel (top)	50	12–25	0.63
	Sand	240	>0.8–2	0.44
	Transition gravel (bottom)	50	5–20	0.43
2	Transition gravel (top)	50	5–20	0.43
	Sand	240	>0.8–2	0.44
	Transition layer (bottom)	50	5–20	0.43
3	Transition gravel (top)	400	5–20	0.43
	Wood charcoal	100	>0.8–20	0.47
	Transition gravel	100	5–20	0.43
	Gravel (bottom)	100	12–25	0.63

The flow applied to the prototype was estimated based on the total volume of greywater generated within Area I and Area III, including all identified greywater sources. The estimated flow was initially used together with hydraulic loading rate (HLR) calculations to obtain an approximate design flow for the system. The HLRs used for the preliminary design were 30, 60 and 80 L/m^2/d, based on values reported for similar filtration systems (Dotro et al., n.d.; Niwagaba et al., 2014).

However, these calculations were primarily used as guiding values. During the testing period of the prototype, the available volumes were sometimes lower than the calculated values. Additionally, the calculations assumed that all greywater generated at the school would be directed to the treatment system. The applied flow was therefore adjusted to the greywater volumes that were practically available during the experimental period, while remaining within the same order of magnitude as the estimated design flow.

Initially, each greywater source was tested separately. However, after several tests with the prototype, it became evident that water from previous runs influenced the quality of subsequent samples. In some cases, this resulted in the effluent appearing more contaminated than the influent. To avoid interference between different water sources, it was therefore decided that only kitchen greywater from the students would be used for the prototype experiments.

Kitchen greywater was selected as it is generated three times per day at relatively fixed times, making it easy to collect, measure and monitor consistently throughout the experimental period. In addition, the quality of the kitchen greywater was observed to be relatively uniform between sampling events, with similar characteristics across different batches. Consequently, the prototype was tested one to two times per day and was intermittently fed with water. This allowed air to re-enter the filter between loading events, promoting aerobic degradation processes (Dotro et al., n.d.).

During each test, influent greywater was collected directly from the kitchen discharge and poured into the prototype as soon as possible after generation. The water quality and volume of the influent were measured with the field instrument, before being applied to the filter. The applied influent volume varied between approximately 1.7 and 5.1 L, with a typical volume in the range of 2.5–3 L per loading event. The effluent was collected from the bottom bucket after approximately 1–4 hours. It was visually inspected and the water quality was measured. The experiments were repeated over 15 days during Phase II to observe the general behaviour and performance of the filtration system. Over this period, the filter was fed with sample water a total of 18 times, of which 13 tests were conducted using greywater from the students' kitchen only. The data for each test was compiled in an Excel sheet and evaluated based on the influent water quality and compared to the effluent quality.

Minor cleaning of the bucket lids and the collection bucket was carried out when necessary to remove small particles and food residues. However, no systematic maintenance of the filter media was performed during the majority of the testing period due to the short operational time.

Towards the end of the experimental period, a decrease in hydraulic performance was observed, with water infiltrating more slowly through the upper layer of the filter. Upon inspection, stagnant water was found in the upper gravel layer, together with visible accumulation of grease and food residues originating from the influent greywater. To restore flow conditions, the upper layer of gravel was removed and rinsed with clean water. In addition, the cotton fabric separating the layers was removed, as it was observed to be clogged. The gravel was subsequently reintroduced without replacing the fabric layer, and the remaining tests were conducted under these modified conditions.

4.6 Social acceptance

Social acceptance of the greywater system was assessed through a questionnaire with staff and students at Tumaini Open School, aiming to capture user perspectives and attitudes.

The questionnaire included questions on participant characteristics, prior knowledge of greywater, and perceptions of greywater reuse. As well as a set of statements which was evaluated using a Likert scale to assess attitudes and perceived risks of greywater reuse. The questionnaire was developed based on a previous study conducted by Al-Khatib et al., 2022, together with relevant factors in the specific local context. The questionnaire form is presented in Appendix B.2.

The questionnaire was distributed to 48 anonymous participants, including both students and staff. It was conducted at the end of the field study for two main reasons. Firstly, to ensure that the questions were formulated to capture aspects relevant to the proposed solution without influencing the participants' responses. Secondly, to build trust with the participants prior to data collection. The questionnaire was translated from English to Swahili to ensure full understanding among all participants.

The results were compiled by calculating mean values and the proportion of participants expressing different responses. Furthermore, cross-analyses were conducted to identify relationships between variables, such as prior knowledge and acceptance of greywater reuse.

The results were used as a basis for evaluating the feasibility of the proposed system beyond technical aspects. It will support the final treatment solution to be dimensioned for the people living at the school and to identify if there was a need for complementary measures such as information and education on greywater reuse.

4.7 Proposed treatment solution

The proposed treatment solution consist of a septic tank and an intermittent sand filter (ISF). The configuration was chosen as ISF only requires small amounts of energy from pumping the water into the filter, which is preferable in a rural environment (U.S. EPA, 1999). The overall conveyance and pumping of the water are outside the scope of this project. Therefore, only the treatment components are included. In general, ISF have low construction costs and do not require complicated maintenance (U.S. EPA, 1999), which is assumed to improve the feasibility of the system.

4.7.1 Water for irrigation

In order to determine which greywater sources should be incorporated into the proposed treatment solution, the irrigation water demand, the generated greywater volumes, and the water quality parameters had to be considered.

To estimate the amount of water required for irrigation of the farming lands, two different approaches were applied and compared. First, the amount of water used to irrigate a single plant was estimated through field observations and discussions with school staff. Subsequently, the number of plants per square metre was estimated based on field inspections. The measured farming land areas included cultivated land, pathways, and currently unused sections within the defined farming plots. Based on the total cultivated farming land, the irrigation water demand was estimated according to Equation 4.8.

$$I_{\text{need}} = A_{\text{cultivated}} \cdot W_{\text{plant}} \cdot D_{\text{plant}} \tag{4.8}$$

where:

- I_{need} = daily irrigation need [L/day]
- $A_{\text{cultivated}}$ = cultivated farming area [m^2]
- W_{plant} = water demand per plant [L/plant]
- D_{plant} = plant density [plants/m^2]

The calculations were performed for several scenarios, including variations in the number of cultivated farming plots (currently cultivated plots and total available farming land), the required water demand per plant (0.5–1 L/plant), and plant density (2–4 plants/m^2).

The second approach was based on the irrigation capacity of the shallow well located on the school property, which was used to estimate an additional approximate irrigation water demand per day. Since the well is sometimes used for irrigation, an irrigation factor was derived from its capacity. Based on discussion with the headmaster, the well provides approximately 1000 L/day and is sufficient to irrigate around 500 m^2. This corresponds to an estimated irrigation factor of 2 L/m^2/day. Using Equation 4.9, the irrigation demand for each area was estimated.

$$I_{\text{need}} = A_{\text{cultivated}} \cdot f_{\text{irrigation}} \tag{4.9}$$

where:

- I_{need} = daily irrigation need [L/day]
- $A_{\text{cultivated}}$ = cultivated farming area [m^2]
- $f_{\text{irrigation}}$ = irrigation factor [L/m^2/day]

When comparing the two calculation approaches, similar magnitudes of irrigation need were obtained, increasing the confidence in the estimated demand. However, since the method presented in Equation 4.9 involved fewer assumptions and uncertainties, these values were used during the dimensioning process.

Based on the irrigation demand and the generated greywater volume calculated in Section 4.3.1, the possible cultivatable area was estimated using Equation 4.10. For Area I, the contribution from the shallow well was also included in the calculations in order to better reflect a realistic scenario where multiple water sources are utilized for irrigation. The average number of rainy days per month was calculated using the data in Table 3.1.

$$A_{\text{GW}} = \frac{V_{\text{GW}} - (I_{\text{need}} \cdot (30 - D_{\text{rain}}))}{30 \cdot f_{\text{irrigation}}} \tag{4.10}$$

where:

- A_{GW} = possible cultivated area irrigated with greywater [m^2]
- V_{GW} = generated greywater volume per month [L/month]
- I_{need} = daily irrigation need for the currently cultivated area [L/day]
- D_{rain} = average number of rainy days per month during the wet or dry season [days/month]

- $f_{\text{irrigation}}$ = irrigation water demand per square metre [L/m^2/day]

4.7.2 Assumed influent greywater quality

For the greywater sources selected for treatment in the proposed system, the most reliable approach would have been to physically mix the selected greywater streams in situ and directly analyse the resulting water quality. However, due to limited time during the field studies, the influent greywater quality was instead estimated through simplified mass balance calculations.

The calculations were performed according to Equation 4.11, based on the estimated greywater flow or volume from each source together with the corresponding measured or estimated water quality parameter for that source (Stockholm Environment Institute, 2025). The mass balance calculations were applied to temperature, turbidity, electrical conductivity (EC), and estimated *E. coli* concentrations.

It is however important to note that these calculations only provide a simplified approximation of the mixed greywater quality rather than exact parameter values. In reality, greywater characteristics vary considerably between different sources and over time depending on factors such as water usage patterns and daily activities (Eriksson et al., 2002).

$$C_{mix} = \frac{Q_1C_1 + Q_2C_2 + \cdots + Q_nC_n}{Q_1 + Q_2 + \cdots + Q_n} \tag{4.11}$$

where:

- C_{mix} = estimated concentration in the mixed influent greywater
- Q_n = greywater flow or volume from source n
- C_n = concentration of the studied parameter in source n
- n = number of greywater sources included in the calculation

For pH, a regular mass balance calculation could not be directly applied since pH is a logarithmic parameter rather than a conservative concentration parameter (Snoeyink & Jenkins, 1980). Instead, an expected influent pH range was estimated based on the lowest and highest average pH values measured for the selected greywater source or sources. This approach was considered sufficient since the guideline range for pH in irrigation reuse applications is relatively wide, between pH 6–9 (Abunaser & Abdelhay, 2020; U.S. Environmental Protection Agency, 2012).

Similarly, for the BOD/COD ratio, an expected range was estimated based on the lowest and highest observed literature BOD/COD ratios for the selected greywater sources, since separate BOD and COD concentrations were not available within the scope of the study. A direct mass balance calculation was not considered appropriate, as the BOD/-COD ratio represents a relationship between two parameters rather than a conservative water quality parameter itself.

4.7.3 Iterative dimensioning of septic tank and ISF

As there are many parameters affecting both the dimensions of the septic tank and filter area, a MATLAB script was created to find the best possible combination within the requirements (see Appendix A.2).

Based on the required greywater volumes calculated in Section 4.7.1, a septic tank and an intermittent sand filter were dimensioned. Since greywater is generated in temporal peaks over the day rather than as a constant flow, the septic tank act as a collection tank to even out the daily peaks. Furthermore, intermittent sand filters require sedimentation as a minimum level design criteria for pre treatment (US EPA, 1980). Therefore, the septic tank will also act as a sedimentation unit where larger particles in the greywater can settle.

The treatment solution was dimensioned based on the estimated greywater generation. A weekly average greywater flow was calculated in order to obtain a representative design value for the entire week. Since the estimated greywater generation was partly based on literature values and assumptions regarding the proportion of greywater generated from total water consumption, a safety factor was included. Based on the sensitivity analysis (see Section 5.2.1), a safety factor of 1.35 was selected to account for the difference between the chosen greywater generation and the highest estimated greywater flow. The design flow (Q_{design}) was calculated by multiplying the safety factor to the weekly average greywater generation. The design flow accounts for uncertainties and variations in greywater generation and reduces the risk of under sizing the treatment system.

The septic tank was dimensioned based on the incoming greywater flow per day (Q_{GW}), the constant design flow (Q_{design}) intermittently dosed onto the filter, and the required storage capacity. The inflowing greywater volume varied temporally throughout the week while the outflow to the filter remained constant in defined doses. The minimum tank volume was determined based on the required storage capacity, the operational retention time, and the maximum daily design flow. The storage was calculated based on a water balance (Equation 4.12), to determine the volume required to buffer temporal flow variations.

$$S_d = S_{d-1} + Q_{\text{GW}} - Q_{\text{design}} \tag{4.12}$$

where:

- S_d = stored greywater volume in the tank at day d [L]
- S_{d-1} = stored greywater volume in the tank from the previous day [L]
- Q_{GW} = generated greywater volume at day d [L/day]
- Q_{design} = constant design flow from the tank to the filter [L/day]

Furthermore, literature suggests a retention time of 24 h (Dixon et al., 2000), which improves water quality through sedimentation. Longer storage times up to 48 h may lead to deterioration of the water quality. The retention time (HRT) is generally calculated as shown in Equation 2.2, however, as the greywater volume in the septic tank varies temporally, a typical HRT could not be determined. Therefore, an average retention time of 24 h was assumed.

With the retention time in mind, the tank would need to have capacity for the largest daily inflow as it will be stored in the tank for one day before filtration. The minimum septic tank volume is therefore based on the maximum storage volume from the water balance in equation 4.12, and the highest daily design flow.

The stored greywater is fed intermittently in doses onto the filter, where the volume of each dose is dependent on the amount of selected doses. In Table 4.3, literature ranges are visualized. However, the chosen range used as input in the MATLAB script is narrowed down to better suit the local context. The required amount of doses in literature, as seen in Table 4.3, are between 2–48. However, A pilot study conducted in a rural area in the Middle East with a similar setup reported that 5–10 doses enabled the best performance (Sabbah et al., 2004). Therefore, the selected range used in the script was between 4–10, which was optimised together with the other parameters.

Table 4.3: Design parameters used for the intermittent sand filter dimensioning. The selected range refers to what was used as input into the MATLAB script.

Parameter	Selected range	Literature range	Source
HLR $[L/m^2/d]$	80–200	80–600	(Sabbah et al., 2004; US EPA, 1980)
Doses [st]	4–10	2–48	(Sabbah et al., 2004; US EPA, 1980, 1999)
Dose depth $[m]$	0.05–0.076	0.05–0.076	(US EPA, 1980)

Each dose should flood the filter bed approximately 0.05-0.076 m (as seen in Table 4.3) according to the design manual by US EPA, 1980. The dose depth is in turn dependent on the filter area, which is also affected by the hydraulic loading rate (HLR). Literature ranges for HLR presented in Table 4.3 varied considerably. The design manual recommended a maximum HLR of 200 L/m^2/d for intermittent sand filters receiving pretreated wastewater from septic tanks (US EPA, 1980). The manual is designed for wastewater in general, therefore, higher HLR could be applicable for greywater treatment systems. However, as presented in Section 2.2.1, a higher HLR can result in a lower effluent water quality and increase the risk of clogging. Therefore, 200 L/m^2/d was selected as the upper design limit.

The MATLAB script used the selected parameter ranges presented in Table 4.3 as input variables. For each parameter combination, the corresponding filter area (A_{filter}, HLR, number of doses (n_{doses}), dose depth (d), and dosing volume (Q_{dose}) were calculated based on the design equations provided in Table 4.4. The MATLAB script is provided in Appendix A.2.

A weighted scoring approach was applied to identify suitable design alternatives. Among the evaluated parameters, HLR and filter area (A_{filter}) were considered the most critical. A higher weighting was assigned to HLR, since it may increase the risk of clogging and reduced treatment performance if too high. The dose depth was influenced by the number of doses as well as the filter area. It was not considered a critical parameter as it was reported as an approximate range (US EPA, 1980) and therefore not included in the score. However, it was manually monitored to ensure it was close to the recommended depth.

4.7.4 Dimensioning of the septic tank

The septic tank was dimensioned as a pre-treatment step before the ISF (US EPA, 1980). Its purpose is to both allow sedimentation of particles and to store and even out the irregular generation of greywater during a day.

Table 4.4: Design equations used in the MATLAB-based dimensioning of the intermittent sand filter and septic tank.

Parameter	Equation	Comment
Q_{dose} [L/dose]	$Q_{\text{dose}} = \frac{Q_{\text{design}}}{n_{\text{doses}}}$	The dose volume decreases with increasing dosing frequency.
A_{HLR} $[m^2]$	$A_{\text{HLR}} = \frac{Q_{\text{design}}}{HLR_{\text{range}}}$	Higher HLR values reduce the required filter area.
A_{dose} $[m^2]$	$A_{\text{dose}} = \frac{Q_{\text{dose}}/1000}{d_{\text{dose}}}$	The required filter area increases with decreasing dose depth.
A_{filter} $[m^2]$	$A_{\text{filter}} = \max(A_{\text{HLR}}, A_{\text{dose}})$	The largest required filter area governed the final filter dimensions.
HLR [L/m^2/d]	$HLR = \frac{Q_{\text{design}}}{A_{\text{filter}}}$	The actual HLR depends on the final selected filter area.
d_{actual} [m]	$d_{\text{actual}} = \frac{Q_{\text{dose}}/1000}{A_{\text{filter}}}$	The resulting dose depth depends on both the dosing volume and filter area.

It was dimensioned with two chambers, where the first chamber generally experiences turbulence due to the inflow of water (US EPA, 1980). At Tumaini Open School, this will be especially prominent during peak greywater generation. Furthermore, it will create calmer conditions in the second chamber where smaller particles can settle. These conditions may also prolong the interval between maintenance and required sludge pump-out. Design criteria for the chamber dimensions can be found in Table 4.5.

The required volume of the tank (Vtank) was based on two components. The first one being the minimum volume calculated in Section 4.7.3, which is estimated to be the active volume (V_{active}) in the tank. The second component included the volume of the sludge (V_{sludge}) which is calculated according to equation 4.13. The two volumes were added together to determine the required tank volume. However, the estimated volume should be considered approximate due to limited available data and the time constraints of the project.

$$V_{\text{sludge}} = P_{\text{sludge}} \cdot n \cdot t_{\text{emptying}} \tag{4.13}$$

where:

- V_{sludge} = volume of sludge before emptying $[m^3]$
- P_{sludge} = sludge production per person [m^3/person/year]
- n = number of persons connected to the tank
- t_{emptying} = emptying interval [year]

The sludge production per person (P_{sludge}) from greywater was reported to range between 18–20 L/person/year (Mohamed, 2011). The number of persons (n) connected to the tank was intentionally overestimated to 100, since the school is expected to grow.

The emptying interval (t_{emptying}) of the tank was based on values found in literature. However, the reported intervals varied significantly, ranging from one month to five years (Halalsheh et al., 2008; Mohamed, 2011; US EPA, 1980), where most studies referred to septic tanks treating general wastewater. Therefore, a conservative emptying interval of one year was selected, in order to assess the actual sludge generation from greywater.

Once the volume was determined, the dimensions of the tanks was decided based on the H:W ratio displayed in Table 4.5, with the aim of making the surface area big with a shallower depth (US EPA, 1980). The septic tank could be dimensioned with concrete with a wall thickness according to the design criteria in Table 4.5. Other materials such as polyethylene, steel and fibreglass are also common materials for septic tanks. The inlet and outlet was dimensioned as T-baffles, with its design parameters displayed in Table 4.5.

Table 4.5: Design criteria used as input for dimensioning of the septic tank

Parameter	Design criteria	Source
Chamber lenghts	Chamber 2 = 1/3–1/2 Chamber 1	(US EPA, 1980)
H:W ratio	1:1	(**Bounds1997DesignTank**)
Distance scum to outlet	>8 cm	(**Bounds1997DesignTank**)
T-baffle above liquid	0.12 x liquid depth	(US EPA, 1980)
T-baffle below liquid	0.26 x liquid depth	(US EPA, 1980)
Concrete thickness	8–10cm	(US EPA, 1980)

4.7.5 Dimensioning of the ISF

The intermittent sand filter (ISF) in both Area I and Area III, was dimensioned based on the output from the iterative calculations in Section 4.7.3.

The thickness of each filter layer was primarily based on the design manual by US EPA, 1980 and compared with values reported in studies with similar configurations and settings, as presented in Table 4.6. The US EPA, 1980 manual discusses the use of upper drainage layers above the sand media in order to reduce surface erosion. However, these layers were excluded in the proposed design, as they are also reported to complicate maintenance procedures, which was considered unsuitable in the local context.

The particle size distribution of each layer is also presented in Table 4.6 together with the corresponding layer. Similarly to the layer thicknesses, the particle fractions were selected based on USEPA manual, previous studies, and the characteristics of the grey-water

Table 4.6: Comparison of filter media configurations reported in literature for intermittent sand filters.

Layer (fraction)	(US EPA, 1980)	(Sabbah et al., 2004)	(Assayed et al., 2010)
Upper gravel [cm]	–	–	10 (11 mm)
Upper transition [cm]	–	–	10 (5 mm)
Sand [cm]	60–107 (0.25–1.5 mm)	87 (0.4–0.6 mm)	60 (0.32 mm)
Transition [cm]	–	7 (0.6–1 mm)	–
Fine gravel [cm]	>8 (0.6–1 mm)	14 (3–5 mm)	10 (11 mm)
Gravel [cm]	>25 (0.6–3.8 mm)	13 (20–40 mm)	10 (11 mm)
Coarse gravel [cm]	–	20	–
Total filter media depth [cm]	–	134	100

The distribution pipes for the ISF were dimensioned according to the design criteria presented in Table 4.7. First, the pipe layout was determined based on the required pipe diameter and lateral spacing. Thereafter, the length of each pipe was calculated using Equation 4.14. The number of orifices varied depending on the pipe length, while the orifice diameter and spacing were selected according to the design criteria in Table 4.7. The design was compared with previous studies by Sabbah et al., 2004 and Assayed et al., 2010 in order to verify that the results were in line with literature in similar settings.

$$L = 2\sqrt{r^2 - y^2} \tag{4.14}$$

where:

- L = pipe length at a given distance [m]
- r = radius of the filter [m]
- y = distance from the centre of the filter area [m]

Additionally, an underdrain system was placed in the drainage layer at the bottom of the filter in order to collect the treated water. The design criteria for the underdrain system are also presented in Table 4.7.

The dosing frequency was selected based on the number of doses calculated in Section 4.7.3 and distributed over a 24-hour period. The dosing interval was based on the estimated daily generation pattern of greywater, with larger peaks occurring around the same time every day. The dosing interval was adapted to the peaks to decrease the load on the septic tank. This approach was used in order to achieve an approximate hydraulic retention time (HRT) of 24 hours in the tank before dosing to the intermittent sand filter.

Table 4.7: Design criteria used for the distribution and underdrain pipe systems in the intermittent sand filter.

Parameter	Design criteria	Source
Distribution system		
Pipe diameter	25–50 mm	(U.S. EPA, 1999)
Orifice diameter	3.2–6.4 mm	(U.S. EPA, 1999)
Head on orifice	0.9–1.8 m	(U.S. EPA, 1999)
Lateral spacing	0.3–1.2 m	(U.S. EPA, 1999)
Orifice spacing	0.3–1.2 m	(U.S. EPA, 1999)
Underdrain system		
Type	Slotted or perforated	(U.S. EPA, 1999)
Underdrain pipe diameter	>100 mm	(US EPA, 1980)
Drain line spacing	3.6 m centre-to-centre	(US EPA, 1980)
Drain line slope	0.5–1 %	(US EPA, 1980)
Ventilation	Vertical pipe upstream	(US EPA, 1980)

4.7.6 Dimensioning of the storage tank

The storage tank was dimensioned based on the estimated number of rainy days during the wet season. As presented in Table 3.1, approximately 100 rainy days occur during the wet season (seven months), corresponding to an average of around 14 rainy days per month or 3.6 rainy days per week. Since no additional irrigation is assumed to be required during rainy days, a conservative scenario was assumed where rainfall occurs during three consecutive days.

Based on this assumption, the storage tank was dimensioned to temporarily store three days of treated greywater generation. The required storage volume was therefore calculated based on the estimated daily treated greywater production for each area.

However, the storage time of treated greywater should be limited, as prolonged storage may result in microbial regrowth and deterioration of water quality (World Health Organization, 2006a). Therefore, the storage tank was intended for short-term storage and balancing of irrigation demand rather than long-term retention of treated greywater.

4.8 Quantitative Microbial Risk Assessment

A Quantitative Microbial Risk Assessment (QMRA) was conducted to evaluate the potential health risks associated with the reuse of treated greywater for irrigation at Tumaini Open School. The method predicts the probability of infection or illness based on pathogen concentrations in the environment and the extent of human exposure through ingestion or contact with contaminated material (Department of Health, 2024). QMRA relies on established relationships between pathogen dose and the corresponding health response and consists of four main components:

1. Hazard identification, where the pathogen of concern and its associated health effects are identified.
2. Exposure assessment, where the pathogen dose an individual is exposed to is estimated.
3. Dose-response assessment, where an appropriate model is selected to describe the

relationship between pathogen dose and the probability of infection or illness.

4. Risk characterization, where the estimated pathogen dose is combined with the selected dose-response model to determine the probability of infection resulting from exposure to the microorganism.

To evaluate whether the estimated health risks are acceptable, QMRA results are commonly compared with established health-based risk benchmarks (Clements et al., 2025; World Health Organization, 2006c). These benchmarks are commonly expressed either as a probability of infection, with a typical target of less than 10^{-4} infections per person per year (pppy), or as Disability-Adjusted Life Years (DALYs), with a commonly applied target of less than 10^{-6} DALYs pppy. DALYs represent the overall disease burden by combining years of life lost due to premature mortality and years lived with disability.

The QMRA was performed using an unpublished software (teaching version) from Chalmers University of Technology of a QMRA water reuse framework for greywater (Knutsson, 2026). The tool includes two potential exposure pathways: ingestion of greywater and inhalation of aerosols. Although the framework is simplified, it can function as an indicator tool to assess whether the proposed barrier system provides sufficient health protection. The program can analyse common greywater reuse scenarios, including handwashing, irrigation, toilet flushing, and food crop production.

The QMRA framework requires input data related to pathogen concentrations, treatment performance, and human exposure scenarios. These input data are pre-defined by the creator of the software and is based on peer-reviewed publications and established guidelines (Knutsson, 2026). The first file contains pathogen-related data and defines different pathogens, literature-reported concentrations in greywater, their impacts on human health, and the accepted DALY target for each pathogen. The second file includes different treatment processes together with their associated log reduction values (LRVs) for different pathogen groups. The final input file defines activities through which humans may be exposed to pathogens. This file includes exposure routes, the expected frequency of each activity per year, and the estimated volume of greywater a person may be exposed to during each event. All input data were modified according to site-specific conditions in order to better represent realistic exposure scenarios.

Mathematically, the framework follows the conventional four-step structure commonly used in microbial risk assessment. Sequential LRVs are applied to the initial pathogen concentration in the greywater to estimate the remaining concentration after treatment (Knutsson, 2026). The resulting concentration is then combined with estimated exposure volumes and frequencies to calculate pathogen doses and probabilities of infection using dose-response models and Monte Carlo simulations. The estimated infection risks and DALYs per person per year are subsequently compared with the WHO health-based benchmarks of less than 10^{-4} infections pppy and 10^{-6} DALYs pppy, respectively. The framework also allows for sensitivity analyses in which selected input parameters, such as pathogen concentrations, treatment performance, and exposure frequency, can be varied to evaluate their influence on the calculated health risks.

For Tumaini Open School, the QMRA analysis was limited to *E. coli* as the only investigated pathogen. *E. coli* was used as an indicator organism for faecal contamination, and pathogen concentrations were based on literature values from similar greywater reuse contexts as found in Section 4.4. The selection of *E. coli* was motivated by its common use in water quality assessments as an indicator of faecal contamination, as it is relatively easy to detect and indicates the possible presence of enteric pathogens (World Health Organization, 2006a). This represents a simplification of the overall microbial risk, since viruses and protozoa are often considered the dimensioning pathogen groups due to their generally higher required LRVs (World Health Organization, 2006c). A more comprehensive QMRA would therefore require the inclusion of reference pathogens from multiple pathogen groups, such as Norovirus, *Cryptosporidium*, and *Campylobacter*. Consequently, the results obtained in this study should be interpreted as indicative rather than as a complete quantitative health risk assessment.

Three exposure activities were analysed in the QMRA framework: garden irrigation (operator exposure), consumption of raw vegetables, and consumption of cooked vegetables. For all three activities, the exposure route was defined as ingestion and the pre-defined volumes for exposure of each activity was used (Knutsson, 2026). This corresponded to assumed ingestion volumes of 0.5 mL during hand-to-mouth exposure associated with irrigation activities, 10 mL during consumption of raw vegetables, and 1 mL during consumption of cooked vegetables. Table 4.8 summarizes the other site-specific input parameters and assumptions used in the QMRA analysis for Tumaini Open School.

Table 4.8: Site-specific input parameters modified for the QMRA analysis at Tumaini Open School.

Parameter	Selected value	Motivation / source
Population exposed	94 persons	Number of exposed students & staff
Irrigation frequency	37 events/person/year	Assumption based on the number of rain-free days and that each person is assumed to perform irrigation once per week during dry periods
Raw vegetable consumption	52 events/person/year	Based on field observations, raw vegetables served approximately one time a week
Cooked vegetable consumption	365 events/person/year	Based on field observations, cooked vegetables served approximately one time per day

The treatment barriers included in the QMRA analysis were selected based on the design of the proposed final greywater treatment solution. Pre-defined LRV values available in the model were initially used as a basis for the analysis. However, several of these values were modified and supplemented with LRVs based on literature data in order to better represent the specific treatment systems evaluated in this study.

Different treatment conditions were also evaluated within the framework, including normal treatment performance, degraded treatment performance, and treatment failure. In the model, normal treatment corresponded to 100% of the predefined LRV values, degraded treatment to 25% removal, and failure to 0% removal. This approach was used to evaluate the sensitivity and robustness of the proposed treatment system under different operational conditions. In addition, separate sensitivity analyses were performed in which selected input parameters in the QMRA model were modified in order to evaluate how changes in model assumptions influenced the resulting health risk estimates.

Additionally, the influence of supplementary treatment and risk reduction barriers was evaluated within the QMRA framework to assess how they affected the estimated DALY values. These analyses focused on the exposure scenarios that, based on the previous QMRA results, were identified as the most sensitive from a health risk perspective. The purpose was to evaluate whether additional barriers could help ensure compliance with the WHO DALY target under future conditions, such as school expansion (up to approximately 450 students), or during degraded and failure conditions within the treatment chain. To better represent such conservative and future scenarios, the 95th percentile DALY values were used in the evaluation instead of the median values. The additional barriers evaluated in the QMRA tool included SODIS (solar water disinfection), biochar filtration, and a change in irrigation method from manual bucket irrigation to drip irrigation (Eawag, 2002; Hagemann et al., 2018; Sidibe, 2014; World Health Organization, 2006a).

5 Results and discussion

This section presents the characterisation and results from the field studies, including greywater quantities and qualities. Additionally, the proposed treatment solution is presented and discussed. Lastly, future studies related to the project is identified and presented.

5.1 Greywater sources

The spatial distribution of greywater generation from showers, handwashing, kitchen activities, and laundry is illustrated in Figure 5.1. The size of the circles represents the relative weekly greywater generation from each source, where larger circles indicate higher volumes.

Figure 5.1: Greywater sources and generation

In Area I, greywater is produced from shower, laundry, handwashing and kitchen activities as seen in Figure 5.1. Showering is done in the sanitary block where the students share 8 washrooms. The plan view of the sanitary block building can be seen in Figure 5.2 (left), as well as the outlets from the showers (right). The greywater is discharged directly outside the building. One of the showers lacks a separate outlet, causing the greywater to be discharged through the adjacent washroom outlet. However, since new showers are currently being constructed in dormitory 2, the greywater flow will be distributed differently in the future. Showering is conducted by filling up buckets at the nearby water tap located in Area I (see Figure 3.3). Then the water is poured onto the body. A bar soap is commonly used during showering. Based on the results from the questionnaire, the mean number of buckets used for showering was 1.28, and on average the students shower 12.74 times per week corresponding to approximately two times per day.

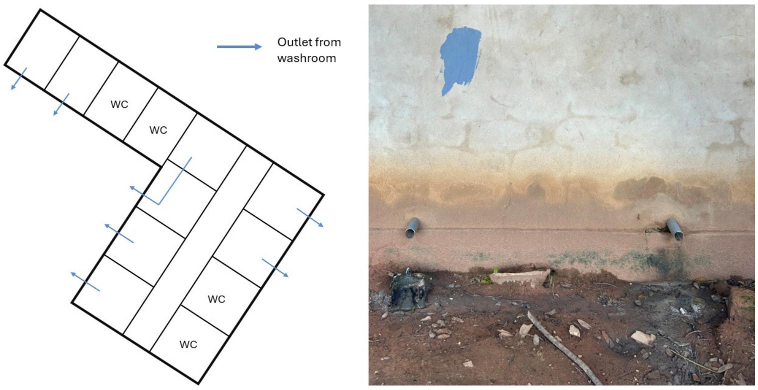


Figure 5.2: Left: Plan view of sanitary block with water outlets. Right: Outlets outside washrooms in sanitary block

In Area I, laundry is carried out using buckets, powdered detergent, and a bar of soap (detailed ingredients list in Appendix A.5). Typically, one bucket is filled with clean water, while another contains water mixed with detergent. Clothes are washed by hand and subsequently rinsed in the bucket with clean water. Based on the questionnaire results, students use an average of 3.03 buckets per laundry session, and laundry is performed approximately 1.89 times per week and student.

Currently, students carry out laundry activities outdoors in areas surrounding the dormitories, as illustrated in Figure 5.3. As a result, greywater is scattered around the area, and is neither produced nor collected at a single, defined location. However, the school is planning to construct a designated laundry area connected to Dormitory 2, equipped with running water as described in Section 3.1. This development is expected to result in a more concentrated greywater production, thereby facilitating easier collection of the water.

Figure 5.3: Approximate representation of where students usually do their laundry

Dishwashing is generated close to the dining hall and often at either the dormitory basin (Figure 5.4 middle) or the dishwashing station (Figure 5.4 right). Based on the results from the questionnaire, both are used mainly for dishwashing whereas a few stated they use them for handwashing as well. However, despite the presence of a designated dishwashing basin, students typically washed their lunch boxes individually by pouring water from the nearest tap and disposing of the wastewater directly onto the ground. Consequently, not all dishwashing greywater could be collected during the measurements.

Figure 5.4: Left: Plan view of dining hall and stations where students are doing their dishes. Middle: Dormitory basin. Right: Dishwashing station.

In Area II, greywater is generated from handwashing and from cleaning activities in the toilets located north of the school building. There are two handwashing basins and four floor drains installed at the facility, as shown in Figure 5.5 (left). Each toilet is equipped with one floor drain, primarily receiving water from cleaning activities, which is discharged through the outlets. Figure 5.5 (right) illustrates where the pipes from the floor drains exit the building and the chambers from the toilets. However, this study only focused on handwashing, since water rarely exited the drains during cleaning activities and was considered negligible.

According to questionnaire results, students wash their hands on average 3.06 times per day at the school (Area II), with an average duration of approximately 7 seconds per event. Based on checklist observations, the usage of the two basins is uneven, as approximately two-thirds of the users prefer the northern basin, with higher flow. Consequently, a weighted average flow rate of 0.012 L/s was estimated.

The handwashing basins were previously connected to pipes that conveyed the greywater directly outside the building (light blue arrows in Figure 5.5). However, at the time of observation, these pipes were either damaged or removed. As a result, the wastewater from handwashing drains directly onto the floor beneath the basins and thereafter flows out of the building. This occasionally resulted in water accumulating outside the entrance. The current drainage paths are illustrated in Figure 5.5 (left), where the outlets in use are indicated.

Area III has similar greywater sources as Area I, including showering, laundry, handwashing, and dishwashing. All greywater generated within the volunteers' house is connected to a septic tank and was therefore not included in the estimated greywater generation.

A lot of greywater is generated in the utility building, as shown in Figure 5.6 (left). The washroom is equipped with a water tap where users fill buckets and pour water over themselves for bathing. The resulting greywater drains into a floor outlet and is discharged through the right pipe, as illustrated in Figure 5.6 (right). The staff typically showers 7 times per week and use an average of 1.5 buckets per shower.

Figure 5.5: Left: Plan view of the toilets north of the school building showing water outlets and drainage paths. Right: Rear view of the toilet building showing the inspection chambers connected to the septic tank, as well as the pipes from the internal floor drains.

Figure 5.6: Left: Plan view of utility building with water pipes and outlets. Right: outlets outside the utility building from washroom (right pipe) and bathroom (left pipe)

Adjacent to the washroom, there is a bathroom equipped with a squat toilet connected to the septic tank. A separate water tap inside the bathroom is used for flushing the toilet, washing hands, and cleaning the floor. The generated greywater drains through a floor outlet and is discharged through the left-hand pipe shown in Figure 5.6 (right).

The utility building also includes a kitchen with a water tap and sink for cooking and dishwashing, where handwashing also occurs during food preparation approximately 4.75 times per day. However, greywater generation from this source is currently limited due to insufficient pipe slope, which frequently causes clogging in the drainage system. When greywater is generated, it is conveyed through the pipes, partly laying underground, before being discharged outside the toilet area, as illustrated in Figure 5.6 (left). This discharge point is located in a confined space between a nearby farm building and a wall, making the area difficult to access.

Due to these limitations, dishwashing is often carried out outdoors by staff or students. Water is collected from the tap next to the municipal water storage tank, and soap or dishwashing detergent is used depending on availability (see ingredients in Appendix A.5). The wastewater is disposed of behind the volunteers' house in a designated drainage channel with a slightly sloped concrete surface, see Figure 5.7. Greywater is introduced into the channel from both ends, after which it is conveyed along the channel by gravity, Figure 5.7 (middle) illustrates the drainage channel. The flow is directed towards outlet pipes that discharge the water to the surrounding planting areas outside Area III, as shown in Figure 5.7 (right).

On average, staff use 4.5 buckets per laundry event and do laundry approximately 1.2 times per week. Manual laundry is similar to the students conducted on various locations in Area III. In contrast to the students, the staff use a liquid detergent, see ingredients in Appendix A.5. The greywater is disposed of at the designated discharge point behind the volunteers' house into the drainage channel, as shown in Figure 5.7.

Figure 5.7: Left: Layout of the volunteers' house indicating the location of the drainage channel and outlet. Middle: Open drainage channel along the backside of the building conveying greywater. Right: Outlet pipes discharging greywater from the channel to the surrounding planting areas outside Area III.

5.2 Greywater volumes and temporal variability

The weekly distribution of greywater generation in Area I is illustrated in Figure 5.8 for laundry, showers, kitchen activities, and handwashing. Based on the results from the questionnaires, observation checklist, and volumetric measurements, a temporal distribution over the week was derived. The figure is divided into five time periods: before breakfast, between breakfast and lunch, between lunch and dinner, after dinner, and night. Greywater production during the night is assumed to be zero in all areas.

The total weekly greywater generation in Area I is estimated to be 6019.30 L/week. Most greywater is generated during the morning and evening periods, and the observed peaks are closely linked to daily routines at the school. Showering and laundry are the largest contributors, producing 3722.60 L/week (61.8%) and 1307.13 L/week (21.7%), respectively. Laundry activities are primarily carried out during the morning hours, while showering typically occurs both before breakfast and after dinner.

Kitchen-related activities mainly occur during scheduled mealtimes and within one hour after meals, resulting in three main flow periods per day. According to the questionnaire responses, both the kitchen and the dormitory basin are used for dishwashing. The estimated greywater volumes therefore appear in both locations, with approximately 474.60 L/week generated in the kitchen (7.9%) and 447.30 L/week in the dormitory basin (7.4%). However, this assumption introduces some uncertainty, as the location where dishwashing takes place may vary from day to day. Furthermore, as previously mentioned, some students wash their dishes directly by the water taps and dispose the greywater onto the ground. While the total volume of greywater produced from dishwashing is expected to remain relatively similar, uncertainties regarding the exact volumes and disposal locations remain.

Handwashing represents the smallest contribution, generating 67.67 L/week (1.1%). This activity occurs continuously throughout the day and therefore does not produce pronounced peaks in the temporal distribution. Handwashing is conducted at various locations across Area I, often directly by the taps. Therefore the location of the generated greywater is not defined at one specific place.

Two major peaks can be observed in Figure 5.8, occurring on Wednesday and Saturday morning. These peaks are mainly driven by laundry activities, which contribute the majority of the flow during these periods. The peak flow reaches approximately 145 L/h on both days during the period before breakfast (06:00–10:00). Due to these concentrated activities, Wednesday and Saturday each account for approximately 19.6% of the total weekly greywater production, which is significantly higher than for the other days of the week.

Overall, shower water represents the largest and most continuous contribution throughout the week, while laundry generates more pronounced peaks at specific times. Kitchen and handwashing activities contribute smaller but more evenly distributed flows. The clear temporal variation in Area I is an important factor to consider when designing the final greywater treatment solution, as variations in production and peak flows influence the system dimensioning.

The weekly distribution in Area II only includes handwashing activities occurring at the toilets located by the school. The weekly distribution can be seen in Figure 5.9. Based on the checklist results, the distribution of flows between the two stations was weighted, as approximately two-thirds of the users chose the northern toilet, which has a higher flow rate. This observation is consistent with the volumetric measurements conducted at the toilets, which showed that the majority of the water was produced at the north station. However, the two toilets are considered as a single greywater flow in the analysis, as the distribution of users between the stations may vary over time.

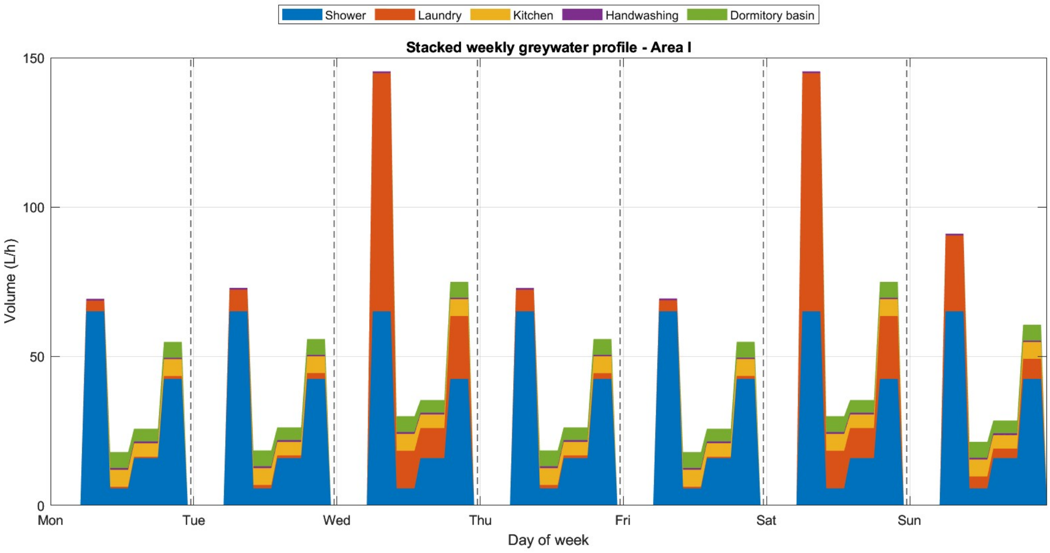


Figure 5.8: Stacked weekly greywater profile in Area I, including shower, laundry, kitchen, handwashing and dormitory basin.

The temporal distribution is assumed to be the same each day as the students spend most their time in and around the school. The total weekly produced volume is 147 L/week with a peak flow of 2.34 L/h, observed between breakfast and lunch (10:00-14:00). The total daily volume from handwashing is calculated to be 21 L/day.

The total weekly volume represents a minor share of the overall greywater production at the school. In combination with the lack of nearby farming areas, Area II was excluded from further analysis. However, the generation in Area II is expected to increase once the laboratory becomes operational and additional water-using activities are introduced. This is however not considered within the scope of the project.

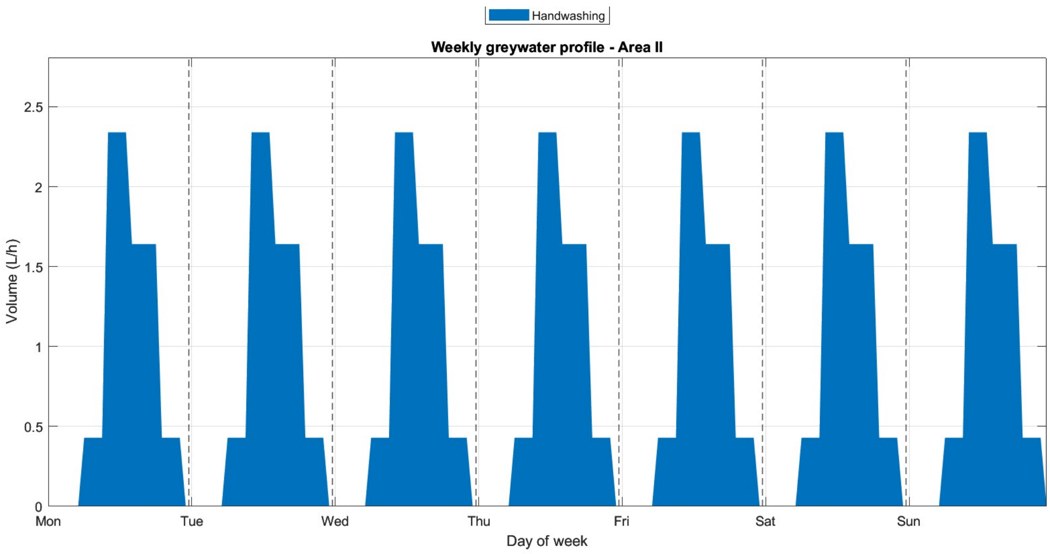


Figure 5.9: Weekly greywater generation in Area II, including handwashing.

Area III consists of the staff housing and the weekly greywater generation is shown in Figure 5.10. The water sources are similar to those in Area I, including showers, laundry, kitchen activities, and handwashing. The volumetric weekly greywater distribution was derived from the questionnaire results and volumetric measurements. The temporal distribution differs to Area I, since the teachers at the school follow a different daily schedule compared to the students. The total weekly greywater flow was calculated as approximately 3360 L/week.

In Area III, laundry produces 474.60 L/week, corresponding to 14.1% of the total greywater production. Laundry is primarily carried out during the weekends based on the questionnaire results. In contrast to the students in Area I, shower water in Area III is only generated before breakfast. The weekly volume from showering is 1845.67 L/week, accounting for 54.9% of the total greywater production.

Handwashing in the bathroom and kitchen contribute 184.57 L/week (5.5%) and 116.67 L/week (3.5%), respectively. The handwashing in the kitchen is assumed to occur one hour before and one hour after typical meal times. Whereas handwashing in the bathroom is assumed to occur evenly during the day. Dishwashing is conducted twice per day in bulk, once before breakfast and once between lunch and dinner, rather than after each meal, as in Area I. It represents the second largest contribution, producing 738.27 L/week (21.96%). In contrast to Area I, where laundry was the second largest source.

There is a certain amount of water that is not included in the calculations. The staff typically rinsed food in water before cooking. In some cases, this was performed over a bucket for food scraps, while in other cases the water was disposed of through a kitchen sink connected to a drainage pipe that was inaccessible for measurements, as shown in Figure 5.6. Since neither of these greywater streams could be measured, they were excluded from the analysis, likely resulting in an underestimation of the total kitchen greywater generation in Area III.

A large peak was identified every day before breakfast, primarily driven by showering activities. However, the highest peak flows occur during weekend mornings before breakfast, when laundry activities also take place. The maximum peak flow was estimated to be 112.08 L/h. Together, Saturday and Sunday account for approximately 19.3% of the total weekly greywater generation.

Overall, the greywater generation in Area III is characterized by lower total volumes although more concentrated peaks compared to Area I. These differences reflect the daily routines of the staff, which was considered when dimensioning the greywater treatment system

Overall, Area I contributes to the largest share of greywater production at the school. The peak flow in Area I (145 L/h) is approximately 30% higher than the peak in Area III (112 L/h), mainly due to the higher number of users. These are larger than the average hourly greywater generation, and therefore need to be considered when dimensioning the treatment system. Area III contributes a smaller but still significant volume, characterized by more concentrated morning peaks related to staff routines. In contrast, the greywater generation in Area II is very limited, consequently, it was excluded from further analysis.

The greywater generation profiles were based on questionnaire results describing the relative distribution of greywater sources, both in terms of magnitude and temporal variation. The daily distributions were divided into five time categories, meaning that no variations within these periods were analysed. This introduces uncertainties regarding the actual hourly greywater generation throughout the week. However, due to time

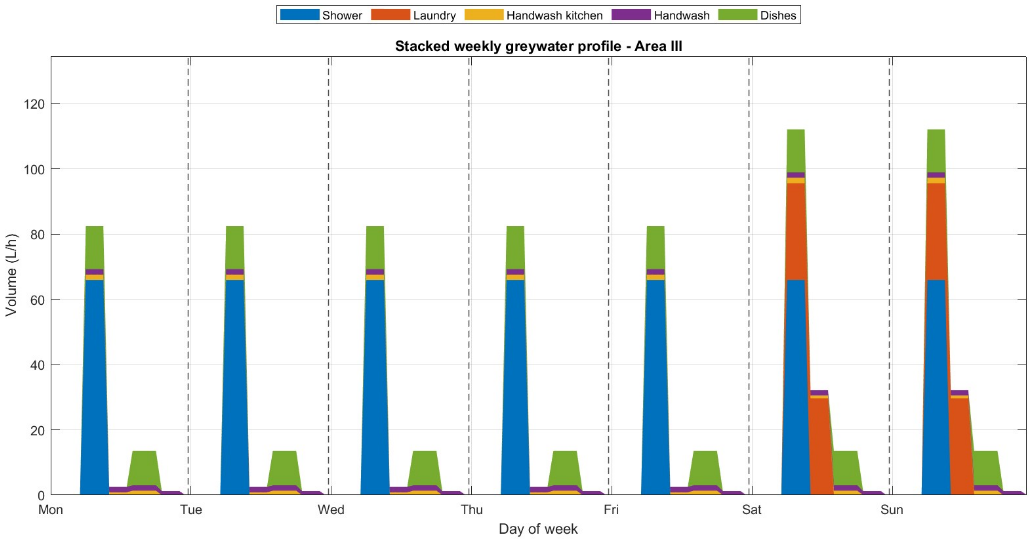


Figure 5.10: Stacked weekly greywater generation and distribution in Area III, including shower, laundry, handwash kitchen, handwash, and dishes.

limitations and the available tools during the fieldwork, a more detailed analysis was not feasible. Furthermore, since the total greywater generation was estimated from water consumption using literature-based values, additional uncertainties are introduced into the calculated greywater volumes.

5.2.1 Sensitivity analysis of greywater generation

A sensitivity analysis was performed for different greywater generation shares of the total water consumption, as shown in Table 5.1. The values of 0.85 and 0.5 represent the highest and lowest values found in the literature. For comparison, the value of 0.6 used in this study is also included together with these extreme cases. The estimated greywater generation increased by 70% when the greywater share was changed from 0.5 to 0.85. The sensitivity analysis highlights that the estimated greywater generation can differ considerably depending on the assumptions made, as well as between the calculated and actual values.

Table 5.1: Sensitivity analysis based on assumed greywater generation share out of total water consumption in Area I and Area III

Greywater generation share	Area I [L/month]	Area III [L/month]
0.5	21500	12000
0.6	25800	14400
0.85	36550	20400

Furthermore, the estimated greywater volumes were used to dimension the proposed treatment system. Therefore, an overestimation of greywater generation could result in an unnecessarily large system design, while an underestimation could lead to insufficient treatment capacity and unused greywater. The uncertainty associated with greywater generation was therefore taken into consideration during the dimensioning of the final treatment solution.

5.2.2 Greywater generation per person

The estimated greywater generation per person is presented in Table 5.2. However, the estimated generation of 10 L/day for students is below the reported range in literature in Table 2.1. Due to the rural setting at Tumaini Open School, values within the lower range are expected. Nevertheless, this may indicate that the estimated greywater volumes are somewhat underestimated. Based on the sensitivity analysis presented in Section 5.2.1, the estimated greywater generation could increase by applying a higher greywater generation factor, resulting in more reasonable greywater generation per person.

Table 5.2: Greywater generation per person at Tumaini Open School

Person	Greywater generation [L/day]
Students	10
Staff	69

5.3 Water quality analysis

The following section present and discuss the characteristics of the greywater generated at the school. The assessment is based on measured parameters, combined with literature values. The analysis provide a broader understanding of the greywater quality and its suitability for treatment and reuse.

5.3.1 Measured pH

The measured pH for the different sources and users are displayed in Table 5.3, together with the standard deviation, minimum values, and maximum values.

Table 5.3: Summary for pH values of the different greywater sources.

Source	pH ($\mu \pm \sigma$)	Min	Max
Laundry students	9.15 ± 1.18	6.30	10.29
Laundry staff	7.26 ± 1.09	6.23	9.81
Handwashing	7.19 ± 0.62	6.28	8.28
Dishes students	7.17 ± 0.70	5.89	8.99
Dishes staff	7.73 ± 1.83	6.35	9.81
Shower students	8.45 ± 0.34	7.99	8.75
Shower staff	7.97 ± 0.02	7.95	7.98

The students used powdered detergent and soap for laundry, and the laundry water from students had a mean pH value of 9.15. Laundry greywater with powdered detergents has previously been reported to have pH values close to 10 (Hardie et al., 2021), which is in line with the findings in this study. However, the measured values varied considerably, ranging from 6.30 to 10.29. These variations are likely related to differences in laundry practices, including the type and amount of detergent or soap used, as well as factors such as the level of dirtiness of the laundry.

In contrast, the laundry water from staff had a lower mean pH value of 7.26 (Table 5.3). The measured values ranged from 6.23 to 9.81, although most measurements were concentrated within the lower range. This difference is related to usage of liquid detergent instead of powdered detergent. Liquid detergents are generally water-based and tend to have pH values closer to neutral (Hardie et al., 2021), which is consistent with the findings for the staff laundry water. In cases where a bar soap was used extensively, higher pH values were observed.

Laundry water have been previously reported to have a pH ranging between 7.1–10 (Li et al., 2009; Uthirakrishnan et al., 2022). Furthermore, the measured values are consistent with previous studies showing that the pH of laundry greywater is strongly influenced by the type of detergent used, with powdered detergents generally resulting in higher pH values than liquid detergents (Shaikh & Ahammed, 2024). The lowest measured pH values for both students and staff were slightly below literature values. Additionally, the highest measured values for student laundry greywater exhibited slightly higher maximum values than those reported in previous studies. However, when considering the mean values, the measured data remained within the reported literature range. These extreme values are likely related to contextual variations and differences in laundry practices. Moreover, manual laundry is considered to generate more polluted greywater compared to washing machines (Shaikh & Ahammed, 2024).

Handwashing water had a mean pH value close to neutral, as seen in Table 5.3. In previous studies, handwashing water is often included within a broader bathroom greywater category, which has been reported to exhibit pH values ranging between 5–8.3 (Li et al., 2009; Uthirakrishnan et al., 2022). In general, the measured pH values for handwashing water were around neutral pH, although the values ranged from 6.28 to 8.28 (Table 5.3). Consequently, the measured values are in line with literature values for bathroom greywater. Soap was not available at the handwashing stations, as students were expected to bring their own soap. However, this was rarely observed during the field studies. Therefore, little to no soap was expected to be present in the handwashing greywater, contributing to the relatively neutral pH values. Handwashing greywater was measured at the bathrooms in Area II and is assumed to be representative for all handwashing activities across the school.

The pH observed in dishwashing water was more similar between staff and students compared to the differences observed for laundry greywater. However, the dishwashing practices differed significantly between the two groups. During the field observations, students rarely used soap when washing their dishes. Therefore, most measured pH values were around 7, although ranging from 5.89 to 8.99 (Table 5.3). The highest pH was measured on one specific occasion with visibly pink water containing large amount of soap. Therefore, it is not representative for the typical dishwashing greywater generated by the students, as it typically lacked soap residues and appeared relatively clear.

Kitchen greywater is often characterized by lower pH values due to contamination from food residues (Bakare et al., 2017). Previous studies have reported pH ranges between 5.9–7.4 for kitchen greywater (Li et al., 2009), while the majority of the measured values in this study were slightly higher. It should also be noted that not all kitchen greywater could be collected, since students often washed their lunch boxes individually and disposed the water directly onto the ground. Thus resulting in less food residues in the collected samples compared to the described kitchen water in previous studies. The missing greywater from dishwashing may have influenced the water quality and the representativeness of the collected samples.

The dishwashing water from staff had a slightly higher mean pH value of 7.73 as seen in Table 5.3, compared to the student dishwashing water. Consequently, it further deviates from the literature values for kitchen activities. However, this is consistent with the field observations, as large amounts of soap were used by the staff when washing dishes, which would be expected to result in elevated pH values.

Shower greywater is typically characterized by elevated pH values due to the presence of soap and personal care products. Previous studies have reported pH values ranging from 6.4–8.1 for bathroom greywater (Li et al., 2009), which includes a broader range of greywater streams rather than only shower water. Another study conducted in South Africa reported a higher mean pH value of 9.24 for bath greywater, connected to soap usage (Bakare et al., 2017).

The shower greywater from students had a mean pH value of 8.45, with a small standard deviation of 0.32, indicating low variation between samples (Table 5.3). The limited variation is further explained by the fact that the students generally used the same type of soap while showering. The measured values are therefore consistent with the upper range reported in the literature. The elevated pH values are likely related to the regular use of soap and personal care products observed during the field study.

Shower greywater from the staff area had a slightly lower mean pH value of 7.97 (Table 5.3), and it remained within the reported range from literature. However, the staff shower water was only measured twice due to difficulties in collecting the greywater, making the dataset less representative compared to the student shower data. Due to the limited number of samples, the measured values might not fully capture the variations in shower greywater from the staff area.

Overall, laundry and shower greywater exhibited the highest pH values, linked to high use of detergents and personal care products. In contrast, handwashing and student dishwashing greywater generally remained closer to neutral, reflecting the limited use of soap observed during the field study. Guidelines for irrigation with reclaimed greywater for food crops eaten raw suggest a pH range between 6–9 (U.S. Environmental Protection Agency, 2012), which is in line with most of the raw sampled data. Therefore, other water quality parameters were considered more critical than pH in the design of the treatment system.

5.3.2 Measured turbidity

The variation in turbidity is illustrated through boxplots in Figure 5.11. The turbidity characteristics, both in terms of data distribution and concentration, differ between students and staff for the same greywater source. The turbidity of greywater varies depending on the source type, with literature reporting values ranging from 20–619 FNU (Edwin et al., 2013; Subramanian et al., 2020; Uthirakrishnan et al., 2022).

Shower water from the students showed relatively high turbidity values, with a mean value of 656 FNU (Figure 5.11). However, most measurements were distributed below the mean, indicating the presence of several elevated values that increased the average turbidity. The shower water from staff exhibited noticeably lower turbidity, with a mean value of 345 FNU, and the data was concentrated within a narrower range. Visual observations further supported these findings, as the students' shower water was typically dark grey in colour, whereas the staff shower water appeared noticeably clearer. It should also be noted that the staff shower water represented only a portion of a sin-

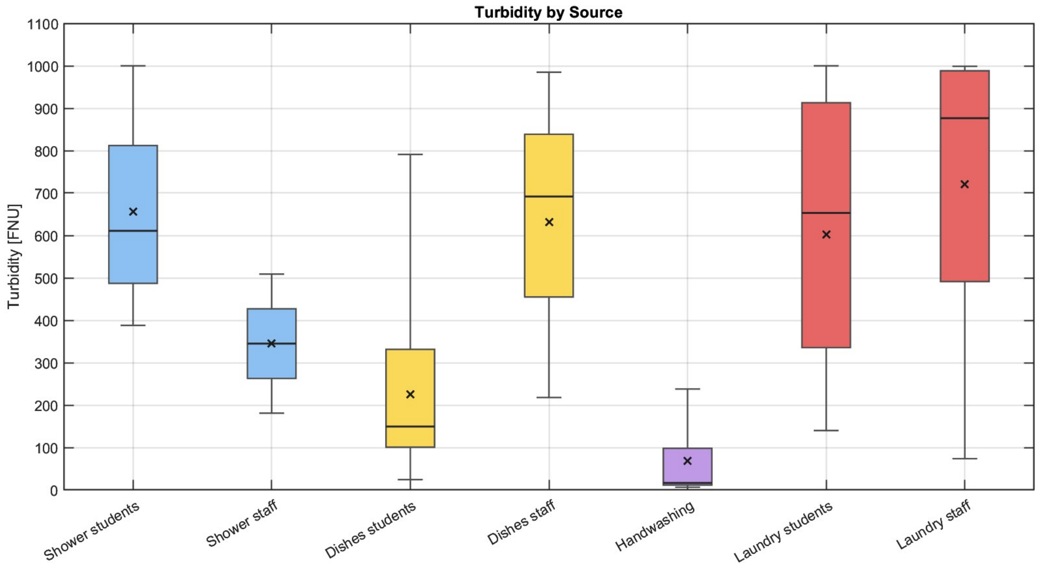


Figure 5.11: Boxplot of turbidity for shower (blue), dishes (yellow), handwashing (purple) and laundry (red), for staff and students.

gle shower event, while the student shower water samples were collected over a longer duration and included greywater from multiple users. This may have influenced the observed turbidity differences between the two sources.

The measured turbidity values from student showers were considerably higher than reported literature values for bathroom greywater, which range between 19–444 NTU (Bakare et al., 2017; Li et al., 2009). This can partly be explained by the local conditions at the school. The washrooms were not fully enclosed, making it easier for dust and debris to enter. In addition, the pathways surrounding the dormitory and washroom areas consisted of fine sandy material. These conditions likely contributed to a greater presence of suspended particles on both the students and within the washrooms, thereby increasing the turbidity compared to typical indoor household bathrooms. This assumption is further supported by the frequent presence of visible sand particles in the buckets used for greywater collection. Additionally, showering was performed using buckets, which generally involves lower water consumption. Consequently, the generated greywater was likely less diluted than in many previous studies, which may partly explain the elevated turbidity values.

The collection buckets were often overfilled with greywater, as many students showered consecutively within a short period of time. In several cases, the buckets remained overnight before sampling due to late showering activities. Consequently, the collected greywater represented an accumulation of water from multiple showers rather than individual shower events. The bucket overflowed as many showers occurred before the collection, thus resulting in loss of some greywater. At the same time, sand and sediments accumulated in the bottom of the bucket and as water continuously overflowed, the remaining greywater may have become increasingly concentrated over time. This could have resulted in the water appearing more contaminated than it initially was.

The student dishwashing greywater had a mean turbidity value of 225 FNU, with most measurements concentrated below the mean, indicating the presence of a few elevated values that increased the average turbidity (Figure 5.11. In some instances, considerably higher turbidity values were observed, with a maximum measured value of 791 FNU. Previously reported turbidity values for kitchen greywater range between 133–298 FNU (Uthirakrishnan et al., 2022). While several of the measured values fell within this range, both lower and higher turbidity values were also observed in this study.

Dishwashing greywater from the staff area exhibited higher turbidity values compared to the student dishwashing greywater, as shown in Figure 5.11. The mean turbidity value for the staff dishwashing greywater was 631 FNU, which is considerably higher than the ranges reported in the literature for kitchen greywater. Compared to the students, the staff consistently used soap and washed dishes in larger batches twice per day. This likely resulted in greywater that was both more concentrated and more representative of the overall dishwashing activity. In contrast, the students often washed their dishes individually and disposed of the wastewater directly onto the ground in smaller quantities at different locations, which may have resulted in less representative samples and lower measured turbidity values.

Handwashing greywater exhibited relatively similar turbidity values across all samples. The mean turbidity value was 68 FNU 5.11, which falls within the literature range reported for bathroom greywater of 19–444 NTU (Bakare et al., 2017; Li et al., 2009). However, some samples exhibited very low turbidity values. This may be explained by field observations indicating that students rarely used soap when washing their hands.

For laundry activities, the difference in measured turbidity values between students and staff was smaller compared to the differences observed for dishwashing and shower greywater. The student laundry greywater exhibited a mean turbidity value of 602 FNU, whereas the staff laundry greywater had a mean value of 720 FNU 5.11. The variability in the measurements likely depended on the amount of clothing washed, whether the water originated from washing or rinsing activities, and at what stage of the washing process the samples were collected. For the staff laundry, samples were consistently collected at the end of the washing process, whereas the sampling time varied for the student laundry. This difference in sampling procedure likely contributed to the lower average turbidity values for students.

Values for laundry greywater have been reported to range between 39–444 FNU (Li et al., 2009; Uthirakrishnan et al., 2022). The measured turbidity values at the school were considerably higher than those reported in previous studies. Large amounts of fine sand and dust were present around the school area, which likely contributed to increased particle content in the water.In addition, washing clothes manually in buckets may result in more concentrated greywater with elevated turbidity values compared to machine washing, where larger water volumes and multiple rinse cycles generally dilute the wastewater (Shaikh & Ahammed, 2020). However, some of the previous studies do not specify whether the reported turbidity values originated from manual washing or machine washing practices. Furthermore, contextual differences also affect the quality of the water.

Compared to irrigation guidelines for irrigation with greywater, turbidity values should according to standards from Jordan remain below 25 FNU (Abunaser & Abdelhay, 2020). None of the sampled greywater sources met this criterion. This highlights the need for adequate greywater treatment to reduce turbidity levels prior to reuse for irrigation.

5.3.3 Measured electrical conductivity

Electrical conductivity (EC) values for shower, dishwashing, handwashing, and laundry greywater from both students and staff are illustrated in boxplots in Figure 5.12. EC and total dissolved solids (TDS) were measured using the same conductivity probe in the multimeter (Hanna Instruments Canada, n.d.). As TDS values are derived from the conductivity measurements, no separate TDS analysis was conducted.

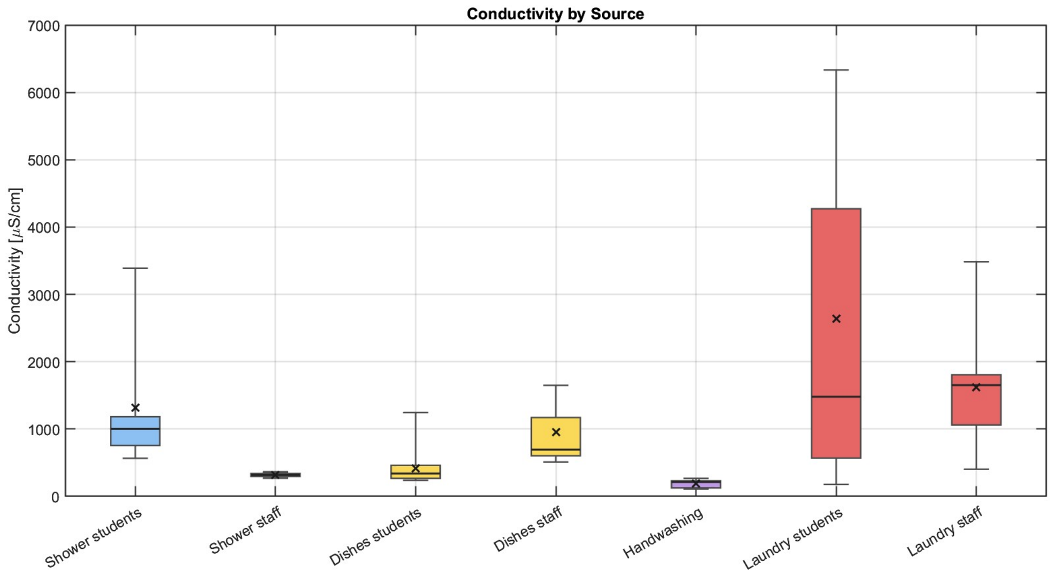


Figure 5.12: Boxplot of electrical conductivity for shower (blue), dishes (yellow), handwashing (purple) and laundry (red), for staff and students.

Shower water from students had a mean value of 1312 μS/cm, the maximum measured value was 3389 μS/cm (Figure 5.12). A range for general greywater have been reported to be between 300–1500 μS/cm (Ghaly, Emam, et al., 2021). However, the mean EC specifically for bathroom greywater has been measured to be 756 μS/cm from a study in Uganda (Katukiza et al., 2015). Elevated EC values are mainly caused by dissolved salts from personal care products such as soap (Yashni et al., 2020). Additionally, a smell of urine was noticed in some of the samples, which could have contributed to the elevated EC values (Maiga et al., 2024). The sample with the highest measured EC value of 3389 μS/cm had a very distinct smell of urine, further indicating that urine contamination contributed to the elevated conductivity.

Furthermore, the local environment at the school may also have contributed to the elevated EC values. The surrounding area mainly consisted of sandy pathways, and visible sand particles were observed in the collected shower water. Soils in the Tabora region contain various minerals and exchangeable cations that could potentially contribute dissolved ions to the water (Mwalembe et al., 2025). Additionally, the use of bucket showering likely resulted in more concentrated greywater due to the lower water consumption, which potentially contributed to the elevated EC values.

The measured mean electrical conductivity of the staff shower water was 318 μS/cm (Figure 5.12), which was considerably lower compared to the student shower water. However, as previously stated, the staff shower samples were collected momentarily during only a short period of the shower event, whereas the student shower samples represented water collected from multiple showers and several students. The measured

EC values from the staff shower are more consistent with values reported in previous literature. However, since only two staff shower samples were collected, no reliable conclusions can be drawn.

The mean EC of the student dishwashing greywater was 411 μS/cm (Figure 5.12), which falls within the typical general greywater EC range of 300–1500 μS/cm (Ghaly, Emam, et al., 2021). However, EC values for kitchen greywater reported in previous studies have varied considerably, with one study conducted in South Africa reporting 320 μS/cm and another study in Uganda reporting 1057 μS/cm (Bakare et al., 2017; Katukiza et al., 2015). This highlights the large variation in conductivity between different locations and greywater characteristics.

The staff dishwashing greywater had a considerably higher mean EC of 951 μS/cm (Figure 5.12), compared to the student dishwashing greywater. This difference was likely related to the amount of soap used during dishwashing, as the staff dishwashing water was often visibly filled with soap in contrast to the student samples.

The measured EC for handwashing was on average 186 μS/cm, which further confirms that little to no soap was used while handwashing. Furthermore, it is less than the reported bathroom values for EC in the study from Uganda with 756 μS/cm (Katukiza et al., 2015). However, compared to the study conducted in South Africa the measured conductivity was 156 μS/cm (Bakare et al., 2017), which is more comparable to this study.

The reported EC in literature have been found to range between 680–1671 μS/cm for laundry greywater (Bakare et al., 2017; Katukiza et al., 2015). Manual laundry, as conducted at Tumaini Open School, has been reported to result in higher EC values compared to washing machines (Shaikh & Ahammed, 2024).

The student laundry greywater had a mean EC value of 2637 μS/cm. However, the measured values showed a large variation, ranging from 177 to 6334 μS/cm (Figure 5.12). Samples with lower conductivity were visually lighter in colour, indicating that limited laundry activities had occurred prior to sampling. Samples with higher conductivity were dark grey in colour, suggesting a higher concentration of detergents and dissolved substances. The staff laundry greywater exhibited lower EC values than the student laundry greywater, with a mean value of 1622 μS/cm (Table 5.12).

The difference between the staff and students can partly be explained by differences in detergent type, as powdered detergents generally produce higher EC values compared to liquid detergents (Hardie et al., 2021; Shaikh & Ahammed, 2024). As seen in Appendix A.3, several sodium based compounds were present in the washing powder used by the students, compared to none in the liquid detergent used by the staff. The sodium content has previously been linked to elevated EC values (Shaikh & Ahammed, 2020), which may further explain the higher EC measured in the student laundry greywater.

In a study conducted in Pune, India, manual laundry using liquid detergent exhibited a mean EC value of 1649 μS/cm, whereas laundry using powdered detergent exhibited a higher mean EC value of 1913 μS/cm (Shaikh & Ahammed, 2020). The students greywater is above the reported range for manual washing with powdered detergent, which could be due to the presence of sand and dust particles. Whereas the staff laundry is in line with the reported literature.

5.3.4 Measured temperature

The temperature of the greywater was relatively consistent between the different sources, with mean values ranging between 23.19–25.4 °C. Since the water was not actively heated and was mainly stored in the muncipal water plastic storage tanks exposed to outdoor conditions, similar temperatures across the sources were expected. Consequently, warm and sunny conditions likely increased the temperature of the stored water and thereby the generated greywater. Furthermore, as the measurements were conducted during the rainy season, greywater temperatures during the dry season (May–October) may potentially be higher due to increased ambient temperatures and solar exposure.

Reported greywater temperatures in previous studies range between 18–38 °C (Ghaly, Abdelrahman, et al., 2021; Tusiime et al., 2022; Uthirakrishnan et al., 2022). The measured temperatures in this study therefore fall within the reported range, although with less variation, likely due to the absence of a heated water system. Elevated temperatures may promote microbial activity and biological degradation processes (Olanrewaju & Ilemobade, 2015). Biological treatment processes are generally considered favourable within the temperature range of approximately 25–30 °C, where both aerobic and anaerobic microbial processes operate efficiently. The measured temperatures were therefore considered suitable for biological greywater treatment.

5.3.5 Measured nitrate

The nitrate concentrations were generally measured within the range of 0–10 mg/L. Since the measurements were conducted using colorimetric test strips, some uncertainty in the results is expected, particularly for values close to the detection intervals of the method. Therefore, some measurements observed at 10 mg/L may have been affected by uncertainties associated with the measuring technique. Greywater typically exhibits relatively low nitrogen concentrations since toilet wastewater is excluded, and urine and faeces are generally the main contributors of nitrogen in domestic wastewater (Jefferson et al., 2004; Li et al., 2009).

However, some of the sampled shower greywater occasionally had a noticeable smell of urine. During one sampling event, the nitrate concentration was measured at 25 mg/L, indicating a contamination of urine to the greywater. This deviates from the conventional definition of greywater, which excludes toilet waste. A study conducted in rural Burkina Faso reported similarly that shower greywater contained urine contamination (Maiga et al., 2024).

5.3.6 Microscopic analysis

As a qualitative complement to the water quality analysis, selected untreated and treated greywater samples were examined using a light microscope. Figure 5.13 presents microscope images of untreated greywater originating from showering (students), dishwashing (students), handwashing (students), and laundry activities (authors of the report). The samples were examined under 10× magnification. Due to the relatively low magnification of the microscope, reliable identification of specific microorganisms, such as *E. coli*, was not possible.

Although no quantitative microbiological analysis could be performed based on the microscope images, the observations allowed for a qualitative comparison between the different greywater sources. As shown in Figure 5.13, the laundry greywater appeared

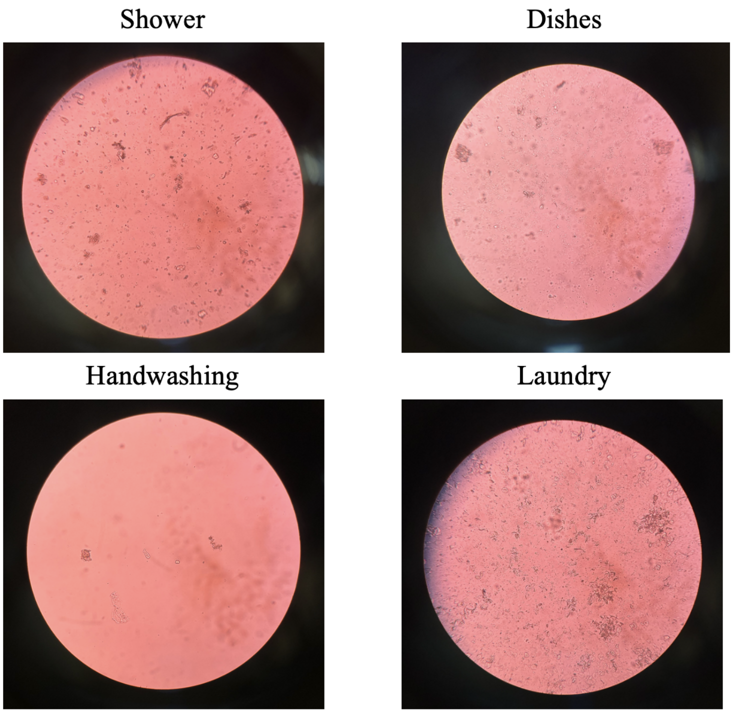


Figure 5.13: Microscope images of greywater generated from showering, dishwashing, handwashing, and laundry activities.

to contain the largest amount of visible particles, followed by shower greywater, dishwashing greywater, and finally handwashing greywater, which appeared to contain the lowest amount of particulate matter. Additionally, the laundry greywater contained contamination from fibres released from clothing during the washing process.

These observations are consistent with the measured turbidity results presented in Figure 5.11, where laundry greywater showed the highest turbidity values and handwashing greywater the lowest. This indicates that the visual particle content observed in the microscope images generally corresponded well with the measured turbidity levels of the different greywater sources.

5.3.7 Comparative assessment of greywater sources

The greywater originating from the students in Area I is considered more contaminated than the staff greywater in Area III. The average measured values for all sources can be seen in Table 5.4.

In Area I, laundry greywater is considered the most contaminated source. It measured the highest average pH and EC with very high maximum values. Additionally, the turbidity of the water had a high average, especially when compared to literature. The second most contaminated source in Area I is the shower. It measured the highest turbidity and second highest pH. The measured EC is however much lower compared to the laundry greywater. In contrast to the laundry, nitrate was detected in the shower greywater. The conclusion that shower greywater was the second most contaminated source deviates from previous literature, where bathroom greywater consistently exhibits lower contamination levels compared to laundry and kitchen greywater (Bakare et al., 2017; Edwin et al., 2013; Ghaly, Abdelrahman, et al., 2021; Li et al., 2009). As

Table 5.4: Average measured water quality parameters for the different greywater sources in Area I and Area III.

Source	pH	Turbidity (FNU)	EC (μS/cm)	Temperature (°C)	Nitrate (mg/L)
Area I					
Laundry	9.15	602	2637	24.46	–
Shower	8.45	656	1312	23.75	25*
Dishwashing	7.17	225	411	25.42	–
Area III					
Laundry	7.26	720	1622	24.68	–
Shower	7.97	345	318	25.05	–
Dishwashing	7.73	631	951	23.19	–
General source					
Handwashing	7.19	68	186	25.25	–

*Measured during a sample with observed urine contamination.

previously mentioned, this is likely linked to the local context and the sampling method.

Similar to Area I, the staff laundry is the most contaminated in Area III. The turbidity and EC is the highest for laundry, whereas the pH is the lowest out of the three sources. However, as seen in Table 5.4, the water quality in the staff area is generally less contaminated compared to the students.

Dishwashing greywater was identified as the second most contaminated source when considering all measured parameters in Area III. The measured turbidity and EC of the dishwater are the second highest as seen in Table 5.4. Thus, the contamination pattern observed in the staff area follows the trends reported in previous literature.

Handwashing occurred in both Area I and III, although the measurements were conducted in Area II. It is considered the least contaminated source. It exhibited a pH close to neutral together with low turbidity and EC values. However, soap was rarely observed during the sampling occasions. Thus, the water quality may vary between the areas and depending on individual handwashing practices.

5.3.8 Estimated BOD/COD ratio

A range for the BOD/COD ratio for laundry, kitchen, and bathroom greywater was estimated based on previous studies in similar contexts. Due to uncertainties and contextual differences, no exact ratio could be assigned from literature. Therefore, three ranges were defined based on the expected biodegradability of the greywater. A BOD/COD ratio below 0.3 is considered to indicate low biodegradability and limited potential for biological treatment (Rudaru et al., 2022). A value between 0.3–0.5 indicates that the water could potentially be treated biologically. Although additional seeding or adaptation of the microorganisms may be required to support the degradation process. Ratios above 0.5 are considered readily biodegradable.

A study conducted by Katukiza et al., 2015 in a peri-urban slum area in Uganda was used as a reference point for comparison. It is expected to be in a similar context in terms of water usage practices, water consumption patterns and limited wastewater management. However, Tumaini Open School is located in a rural area further away from the city which might impact some practices and local variations. Table 5.5 presents the BOD/COD ratios from the study, together with the assumed range for Tumaini Open School.

Source	BOD/COD	Comparability	Assumed range
Area I			
Laundry	0.24	Similar	< 0.3
Kitchen	0.33	Slightly lower	< 0.3
Bathroom	0.31	Slightly lower	< 0.3
Area III			
Laundry	0.24	Slightly higher	0.3–0.5
Kitchen	0.33	Similar	0.3–0.5
Bathroom	0.31	Slightly lower	< 0.3

Table 5.5: Assumed range of BOD/COD ratio compared to literature values from Katukiza et al., 2015

The BOD/COD ratio for laundry was 0.24 in the study (Katukiza et al., 2015). The students in Area I at Tumaini Open School use a powdered detergent which often contains higher concentrations of organic compounds compared to liquid detergents (Shaikh & Ahammed, 2024). This can also be observed in the detergent ingredients when comparing powdered to liquid detergents (see Appendix A.5). Consequently, the use of powdered detergent produce greywater with increasingly elevated BOD and COD values compared to liquid detergents. The perfume and brighteners in the powdered detergents used in Area I can also contribute to higher COD levels. Therefore, the students laundry greywater is expected to have a similar or even lower BOD/COD ratio than 0.24 as found in the study by Katukiza et al., 2015. Therefore, the assumed range for the laundry water from students in Area I is considered to be < 0.3 as displayed in Table 5.5.

A study conducted in Pune, India by Shaikh and Ahammed, 2024, reported similar EC values to the measured conductivity in this study. Additionally, the context was similar with manual handwashing and usage of liquid detergent. However, other parameters differed slightly from the measurements in this study. Through the reported BOD and COD values from the Indian study, a BOD/COD ratio of 0.52 was calculated (Shaikh & Ahammed, 2024). Compared to the BOD/COD ratio of 0.24 reported for laundry greywater by Katukiza et al., 2015, the staff laundry greywater in this study likely exhibits a biodegradability somewhere between these reported values. Therefore, the BOD/COD ratio is expected to be somewhere between 0.3–0.5, indicating that the greywater could be treated biologically (Rudaru et al., 2022).

The BOD/COD ratio for kitchen greywater was 0.33 in the reference study (Katukiza et al., 2015). However, when comparing the measured water quality parameters between the study conducted in Uganda with this study, substantial differences were observed. Another study conducted in a similar low-income peri-urban setting in South Africa by Bakare et al. (2017) reported parameters more comparable to the student dishwashing greywater in this study. The reported BOD/COD ratio in the South African study was 0.29. Therefore, the student dishwashing greywater in this study is expected to exhibit a BOD/COD ratio between the Ugandan and South African study, within the range of 0.29–0.33. However, values closer to 0.29 are considered more likely, since several parameters were within a similar range to those reported in this study. Therefore, the dishwashing greywater in Area I is considered to have low biodegradability, as presented in Table 5.5.

A BOD/COD ratio of 0.33 for kitchen greywater was reported by Katukiza et al. (2015). When comparing the water quality parameters, the staff dishwashing greywater in this study appears relatively comparable to the reference study. Therefore, the BOD/COD ratio for the staff dishwashing greywater is expected to be close to 0.33 and falls within the range of 0.3–0.5 as seen in Table 5.5, which indicates moderate biodegradability.

Shower in Area I was identified as the second most contaminated source at the school. When compared to the laundry greywater in the reference study by Katukiza et al., 2015, similar pH and turbidity values were observed, although the EC values were higher for the laundry greywater. The reference study reported A BOD/COD ratio of 0.31 for bathroom greywater. However, the measured EC values in this study were more comparable to the laundry greywater than to the bathroom greywater reported in the reference study. Therefore, the BOD/COD ratio of the shower greywater is likely to fall between the reported values for laundry greywater (0.24) and bathroom greywater (0.31). The BOD/COD ratio is conservatively assumed to be within the lower biodegradability category defined in this study (see Table 5.5).

The shower greywater in the staff area was considerably less contaminated compared to the student shower greywater. A BOD/COD ratio of 0.31 for bathroom greywater was reported by Katukiza et al. (2015), whereas Bakare et al. (2017) reported a lower BOD/COD ratio of 0.13 for bath greywater. Neither of the studies reported water quality parameters fully comparable to the staff shower greywater measured in this study. Nevertheless, the BOD/COD ratio for the staff shower greywater is expected to fall within the lower biodegradability category and likely below 0.3, as presented in Table 5.5.

5.3.9 Estimated *E. coli* concentrations

E. coli concentrations were estimated based on reported literature values from similar contexts for laundry, kitchen, and bathroom greywater. *E. coli* was selected since it is commonly used as an indicator organism for overall fecal contamination (World Health Organization, 2006a). It is of particular importance when evaluating suitability for irrigation according to reuse guidelines (World Health Organization, 2006b).

The study conducted in a similar context in Uganda by Katukiza et al. (2015) reported *E. coli* concentrations for different greywater sources. As presented in Table 2.4, laundry and bathroom greywater contained 1.44×10^6 and 2.35×10^6 cfu/100 mL, respectively. Since few studies from contexts comparable to Tumaini Open School were identified, these values were considered representative estimates for this study (Table 5.6). When compared to reported *E. coli* concentrations in studies conducted in England (Jefferson et al., 2004) and New Zealand (Leonard et al., 2016), the Ugandan study reported considerably higher concentrations as seen in Table 2.4. This indicates that greywater generated in rural contexts may exhibit elevated microbial contamination levels. Furthermore, the comparison highlights that *E. coli* concentrations in greywater are highly context dependent, making it more appropriate to compare values with studies conducted under similar local conditions.

Kitchen greywater did not contain detectable *E. coli* concentrations in the Ugandan study (Katukiza et al., 2015). However, a study conducted in Jordan by Halalsheh et al. (2008) reported kitchen sink concentrations of 7.0×10^5 cfu/100 mL (Table 5.6). Since *E. coli* is an important parameter when evaluating irrigation suitability, the Jordanian values were included to represent a conservative or worst-case scenario.

Source	E. coli	Unit	Reference
Laundry	1.44×10^6	cfu/100mL	(Katukiza et al., 2015)
Bathroom	2.35×10^6	cfu/100mL	(Katukiza et al., 2015)
Kitchen	7.0×10^5	cfu/100mL	(Halalsheh et al., 2008)

Table 5.6: Estimated *E. coli* concentrations based on previous studies

5.4 Prototype performance

The performance of the prototype, based mainly on kitchen greywater, during the 15-day operational period of Phase II is summarized in Table 5.7. The table presents average influent and effluent water quality in relation to relevant irrigation guidelines.

Table 5.7: Average influent and effluent water quality measured during prototype operation, compared to relevant irrigation guidelines.

Parameter	Unit	Influent	Effluent	Guideline	Source
Turbidity	FNU	261	19	25	(Abunaser & Abdelhay, 2020)
pH	–	7.0	7.7	6–9	(U.S. Environmental Protection Agency, 2012)
Conductivity	μS/cm	494	796	<700[a]	(Food and Agriculture Organization of the United Nations, 2003)
Total dissolved solids	mg/L	247	398	<450[a]	(Food and Agriculture Organization of the United Nations, 2003)

[a] Corresponds to "no restriction" classification for irrigation water quality.

The prototype resulted in a clear improvement in water quality for all measured parameters, although the degree of compliance with guideline values varied between parameters. Visually, the influent greywater was observed to be grey to light grey in colour, often turbid and occasionally foamy. In contrast, the effluent appeared substantially clearer and less turbid. Figure 5.14 presents a visual comparison of greywater before and after filtration through the prototype.

For turbidity, a substantial reduction was achieved, decreasing from an average of 261 FNU in the influent to 19 FNU in the effluent, as seen in Table 5.7. This corresponds to an average removal efficiency of 87.9%, and indicates effective particle removal within the filter. When compared to guideline values, it should be noted that recommended limits vary significantly depending on the context. Stricter guidelines, such as those

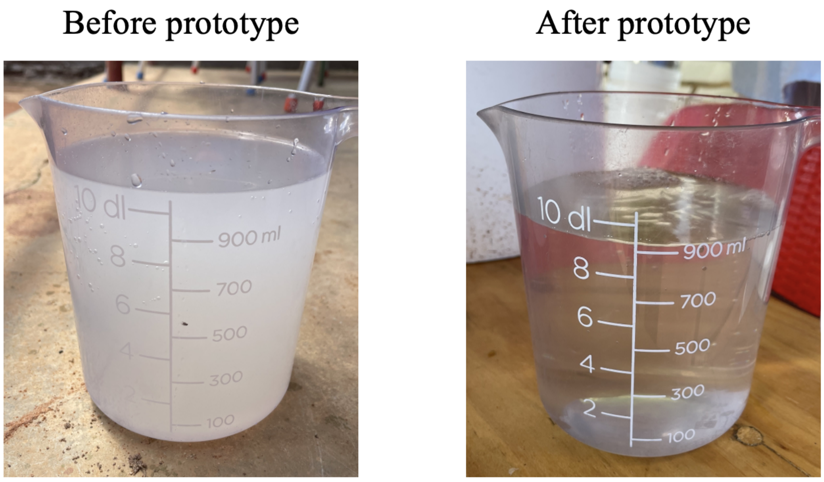


Figure 5.14: Visual comparison of greywater before and after filtration through the prototype.

from USEPA, suggest turbidity levels below 2 NTU for irrigation of crops consumed raw (U.S. Environmental Protection Agency, 2012). However, such standards are developed for highly treated wastewater and may be considered overly stringent for decentralized greywater systems in low-resource settings.

In contrast, Jordanian standards for reclaimed greywater allow turbidity levels up to 25 FNU (Abunaser & Abdelhay, 2020). This context is considered more comparable to the conditions at Tumani Open School. Based on this threshold, the average effluent of the prototype meets the guideline value for turbidity, suggesting that the treated water is suitable for irrigation use under similar conditions.

Treatment performance was further evaluated as a function of cumulative bed volumes (BV), based on the active filter media volume (sand and charcoal). The turbidity removal for the sand filter is presented in Figure 5.15, while the corresponding results for the charcoal filter are provided in Appendix C, Figure C.1.

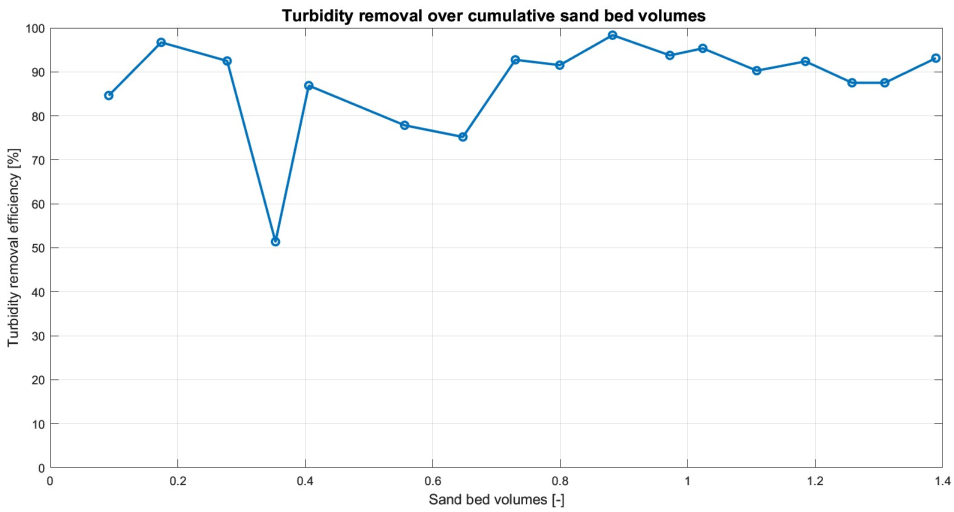


Figure 5.15: Turbidity removal [%] over cumulative sand bed volumes.

Both the sand and charcoal showed a relatively stable turbidity removal efficiency of approximately 85–95% throughout the operational period. However, this performance was observed over different ranges of treated bed volumes. The sand filter was operated up to approximately 1.4 bed volumes, whereas the charcoal filter reached a higher number of approximately 6.7 bed volumes. This difference is attributed to the smaller volume of the charcoal layer compared to the sand layer, resulting in a higher relative loading rate when expressed in bed volumes.

A temporary decrease in removal efficiency to approximately only 50% was observed in both datasets. Prior to this measurement, the same influent sample had been recirculated through the filter four times. This deviation of low removal rate can therefore be attributed to this specific test condition. The approach with recirculation was initially used to assess filter behaviour under repeated loading. However, it was not considered representative of normal operating conditions and was therefore excluded from the turbidity removal analysis. In addition, the influent turbidity of this sample was relatively low (50 FNU) compared to other samples with significantly higher initial turbidity (average 261 FNU). As a result, the calculated removal efficiency appears lower, despite the effluent turbidity (25 FNU) being comparable to the average effluent value of 19 FNU.

These results indicate that the apparent drop in removal efficiency could be influenced both by experimental conditions and by the relatively low influent turbidity, rather than reflecting a fundamental decline in filter performance. Apart from this deviation, the overall stability in turbidity removal suggests that the system maintained consistent particle removal during the initial phase of operation. However, as the system was only operated up to approximately 1.4 bed volumes for the sand filter and 6.7 bed volumes for the charcoal filter, the results primarily reflect short-term performance. Consequently, longer-term behaviour or sustained clogging cannot be fully assessed.

As seen in Table 5.7, the pH of the prototype effluent increased slightly from 7.0 to 7.7 after treatment but remained within the recommended range of 6–9 for irrigation (U.S. Environmental Protection Agency, 2012). The increase in pH may partly be attributed to the presence of charcoal in the filter, as charcoal materials are known to have alkaline properties and can release basic compounds into the water (Musa et al., 2020). Despite this increase, the effluent remains within acceptable limits and is therefore unlikely to negatively affect irrigation suitability.

The average electrical conductivity (EC) increased from 494 to 796 μS/cm after treatment, indicating an increase in dissolved ions in the water. Slow sand filtration is known to effectively remove suspended solids and turbidity, while dissolved constituents are not removed to the same extent (Saini et al., 2021).

A similar increase in EC was reported by Niwagaba et al. (2014) following greywater treatment in a pilot system primarily consisting of charcoal. The authors suggested that the increase could be related to the conversion of organic phosphorus and nitrogen into orthophosphate and mineral nitrogen, thereby increasing the concentration of dissolved ions in the water. A similar mechanism may have contributed to the increase observed in this study, although no measurements of phosphorus or nitrogen were conducted and the exact cause of the increase in EC therefore remains uncertain.

In addition, observations from the experimental data suggest a carry-over effect between successive loading events. When water with relatively high EC, such as laundry water used in the initial tests, was applied to the filter, a decrease in EC was observed after treatment. However, subsequent samples with lower initial EC showed an increase after passing through the prototype. This indicates that dissolved substances, such as soaps and detergents, from the previous laundry loading, may accumulate within the filter and later be released into following samples.

The effluent EC of 796 μS/cm exceeds the threshold for no restriction (<700 μS/cm) presented in Table 5.7, and instead falls within the range corresponding to slight to moderate restriction for irrigation use (Food and Agriculture Organization of the United Nations, 2003). This suggests that while the treated water remains suitable for irrigation, some consideration may be required depending on site-specific conditions such as soil type, crop sensitivity, and irrigation practices. Elevated EC indicates increased salinity, which may negatively affect plant growth by reducing water uptake and, over time, lead to salt accumulation in the soil (Bakare et al., 2017).

Salt accumulation is particularly relevant in semi-arid regions such as Tabora, where high evaporation rates can promote the build up of salts in the root zone (FAO, 1985). Therefore, future implementation of a greywater treatment and reuse system would benefit from a more detailed assessment of salinity-related risks.

Total dissolved solids (TDS) increased from 247 to 398 mg/L after treatment, following a similar trend as observed for conductivity. This is because both parameters were measured using the same conductivity probe, where the TDS values were estimated from the EC measurements by the instrument (Hanna Instruments Canada, n.d.). However, TDS was still analysed and compared to irrigation guidelines to evaluate the irrigation suitability. When compared to irrigation guidelines, the effluent TDS concentration remains below the threshold for no restriction (<450 mg/L) according to FAO classification (Food and Agriculture Organization of the United Nations, 2003). Although the TDS values meet the guideline for no restriction, the combined increase in dissolved solids and conductivity indicates a potential risk of salinity build-up over time.

In addition to the measured water quality parameters, the prototype performance was also qualitatively evaluated through microscopic analysis. The analysis was performed for dishwashing greywater generated by students, before and after filtration through the prototype. Figure 5.16 presents the microscope images, where a visibly lower amount of particulate material can be observed in the treated sample compared to the untreated sample. This observation is consistent with the results discussed previously in this section.

One observation from the microscopic analysis was that moving organisms were detected in the treated sample after filtration through the prototype. Due to the relatively low magnification of the microscope and the lack of microbiological identification methods, it was not possible to determine the exact type of organism observed. According to the laboratory technicians at the hospital, the organisms could possibly have been protozoa. Protozoa are a group of microorganisms that can occur naturally in greywater and aquatic environments, and some species are associated with waterborne diseases (Budeli & Sibali, 2025). However, not all protozoa are harmful to humans, and many species are naturally occurring organisms that do not pose a risk to human health (Health Canada, 2019).

From the observations, no reliable conclusions regarding the presence, absence, concentration, or species identity of protozoa could be drawn. Additional microscope samples

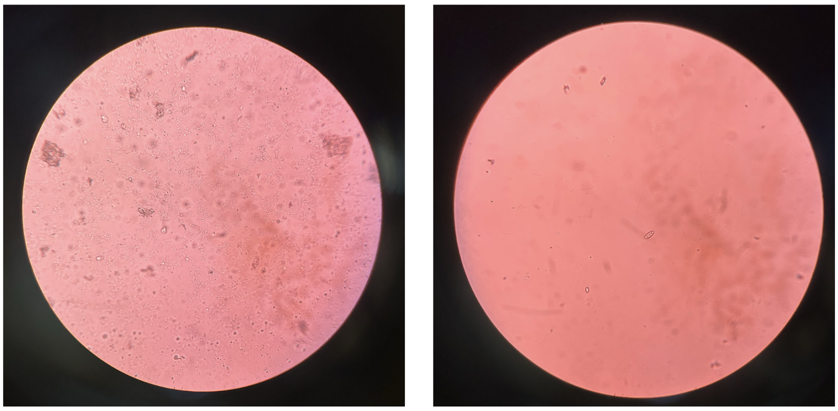


Figure 5.16: Microscope images of dishwashing greywater before and after filtration through the prototype.

and higher magnification would have been required to provide a more reliable assessment of the microbial content in the greywater before and after treatment.

Overall, the results indicate that the prototype performs effectively during initial operation, particularly in terms of turbidity removal, where consistently high removal efficiencies were achieved. The system also produced effluent that meets relevant irrigation guidelines for turbidity and pH, while EC and TDS indicate a slight increase in salinity that may require consideration under long-term use.

The observed variations also indicate that the system performance may be sensitive to changes in influent characteristics and loading conditions. However, the experimental period was limited to 15 days with relatively low cumulative loadings of approximately 1.4 bed volumes for the sand and 6.7 bed volumes for the charcoal. As a result, the findings primarily reflect short-term performance, and do not capture longer-term processes such as sustained clogging or filter maturation. Further testing under extended operational periods is therefore required to assess the long-term stability and robustness of the system, as well as its suitability for continuous use in the intended context.

The prototype results indicate that a greywater treatment system using locally available materials has promising potential within the studied context. Despite the simple design and short operational period, the system achieved stable turbidity removal and produced effluent that generally complied with relevant irrigation guidelines. This suggests that greywater generated at Tumaini Open School has the potential to be treated using a decentralized sand- and charcoal filter. The prototype also provided a practical basis for the development of a full-scale treatment system.

The prototype was not intended to directly determine the exact dimensions or configuration of a full-scale system. Instead, it was primarily used to evaluate whether a greywater treatment system using mainly sand could function under the studied conditions. In addition, the partial clogging observed towards the end of the operational period highlighted the importance of including pre-treatment steps in a future full-scale system to reduce solids accumulation and improve long-term operational stability.

5.5 Social acceptance

The public perception of greywater reuse varied among the respondents. Greywater was known by 62 % of the participants, which is quite high given the local context where greywater reuse is not common. However, since the survey was conducted during the later stages of the field studies, it is possible that many respondents had been exposed to the project and therefore become familiar with the term greywater. No clear relationship between prior knowledge of greywater and willingness to reuse greywater was seen. This differs from literature where previous studies found that knowledge often correlates with willingness. Nevertheless, even if the term greywater was familiar to the respondents, the concept of greywater reuse itself may still have been unfamiliar, which could partly explain the results.

The acceptance of greywater reuse for different applications varied, as shown in Figure 5.17. Overall, all applications showed relatively high acceptance rates. Construction purposes and irrigation of trees had the highest acceptance, with 81% and 79% of the respondents answering yes, respectively. Irrigation of crops showed a slightly lower acceptance, where 67% were comfortable with the reuse application. This is likely related to perceived health risks, since crop irrigation may involve more direct exposure through edible produce compared to construction purposes and tree irrigation.

The comfort of reusing untreated greywater for irrigation had a mean value of 2.14 on the Likert scale. When the same question was asked regarding treated greywater, the mean value increased to 3.95. This indicates that treatment of the greywater significantly increases the acceptance of reuse. Therefore, the acceptance levels presented in Figure 5.17 could potentially increase further if the greywater is properly treated before reuse.

Toilet flushing had the lowest acceptance rate, at 61%. This can likely be explained by the more direct human contact associated with this activity. Water is used for both personal cleaning and washing. Therefore, it is reasonable that the acceptance was lower, as direct contact with greywater has previously been shown to decrease public acceptance.

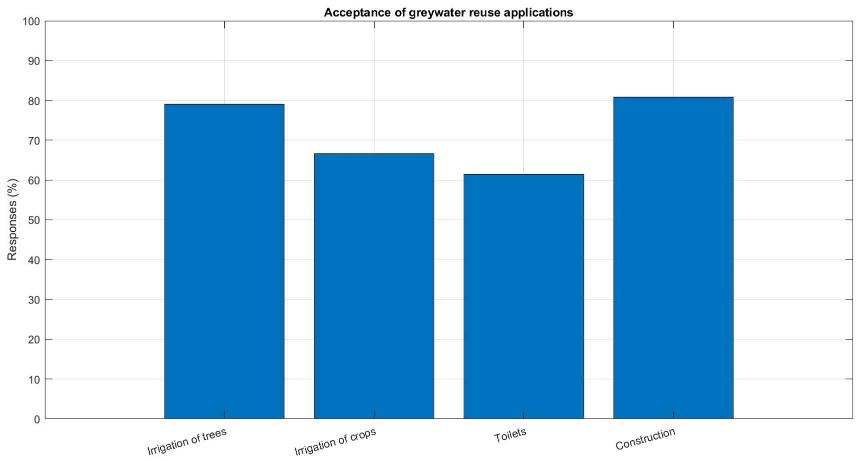


Figure 5.17: Reuse acceptance for different activities.

The concerns associated with greywater reuse is displayed in Figure 5.18. Health risks were the major concern among the respondents, with 62% expressing worry. Smell, water quality and environmental effects appeared to be less significant. Among the respondents expressing health risk concerns, clear information about safety and training on how to use the reuse system were identified as the most important measures for increasing acceptance. Only a small proportion selected treatment of the water itself as the main factor that would increase their comfort with reuse. This highlights the importance of information and education prior to implementation. Acceptance is not only related to treatment of the greywater, but also the understanding and trust in the system. .

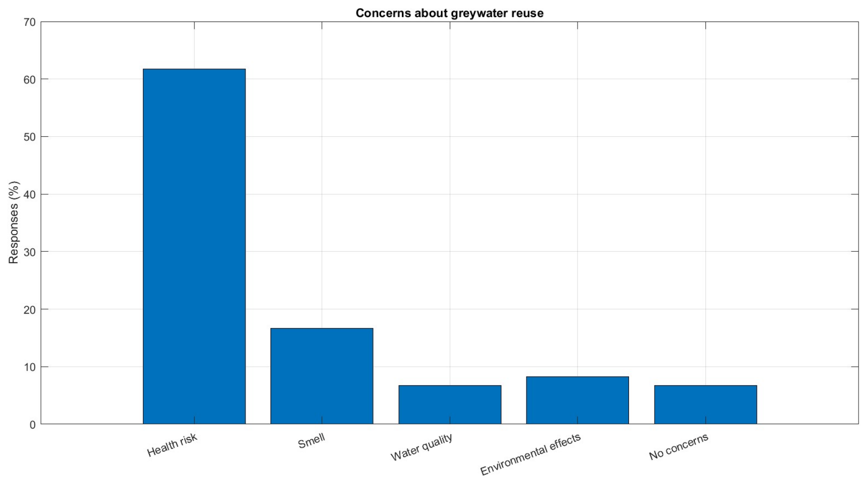


Figure 5.18: Concerns associated with greywater reuse according to the survey responses.

Trust in the treatment system was positively associated with willingness to reuse greywater. Respondents expressing higher trust in the treatment system tended to report greater willingness to reuse greywater for irrigation. Therefore, increasing trust in the system could likely improve the acceptance and long-term success of greywater reuse systems. As previously discussed, trust was found to be strengthened through education and training prior to implementation. Consequently, user manuals, operation and maintenance guidelines should be included as part of the proposed technical solution. This is further elaborated in Section 5.6.7.

In addition, some respondents expressed cultural concerns related to greywater reuse. According to them, used or contaminated water are associated with medicinal practices or cultural rituals in certain settings. However, it remains uncertain to what extent such beliefs influence greywater reuse at the school or how widespread these practices are within the local context. Nevertheless, the responses highlight the importance of considering cultural aspects and local perceptions when evaluating the reuse potential and implementing greywater reuse systems.

5.6 Proposed treatment solution

The proposed greywater treatment solution for Tumaini Open School will be described in the following section. The treatment system consists of a septic tank, intermittent sand filter (ISF) and a storage tank.

Two separate treatment systems are proposed to be designed, one for Area I and one for Area III (see location in Figure 5.19). As seen in the figure, the farming lands are distributed across the school premises. The use of two separate treatment systems therefore enables local reuse of greywater for irrigation, making the conveyance of water from the source to the treatment system and thereafter to the farming lands both shorter and simpler. The division into two separate systems also enables the project to be implemented in phases, which is preferable in the local context where funding may be limited and provided gradually. The system in one area could therefore be evaluated with respect to its treatment performance, operational feasibility, and user acceptance before expanding the implementation with a treatment system to the second area. Furthermore, since the load on each filter will be lower, maintenance may be required less frequently compared to one large centralized filter treating greywater from both areas.

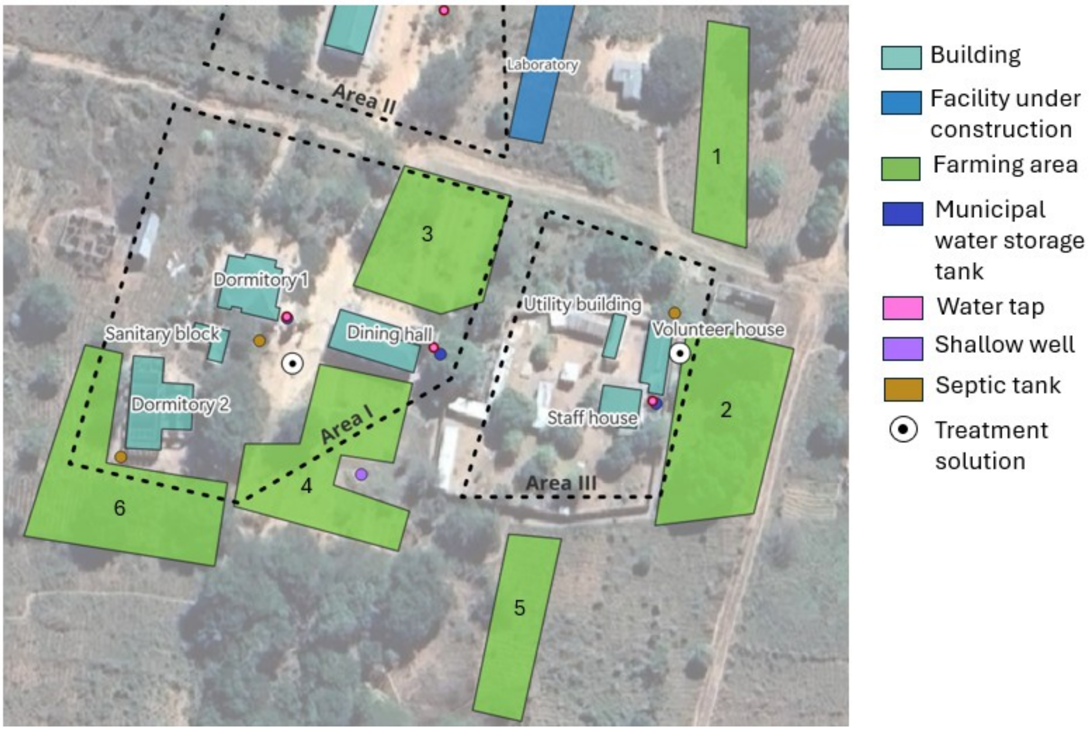


Figure 5.19: Location of proposed treatment systems in Area I and Area III

5.6.1 Irrigation need

The irrigation demand was calculated for Area I and Area III during both the wet and dry seasons. The calculations were based on the measured areas of the farming lands observed during the field studies (see Table 3.3), together with the estimated irrigation water demand per square metre. Since maintaining a consistent food production throughout the year is desirable, the farming areas cultivated during the wet season were also assumed to be cultivated during the dry season in Table 5.8.

The irrigation demand exceeded the available greywater generation in all scenarios except one, as shown in Table 5.8. Therefore, all greywater sources were included when dimensioning the treatment solution to maximise the reuse potential. However, due to varying water quality it could be advantageous to exclude the most contaminated sources, such as shower and laundry. By doing that, the contaminant load on the filter would be less. Although this would be desirable from a water quality perspective, the volumes generated from showers and laundry account for 84% and 69% of the total greywater generation in Area I and Area III, respectively. By excluding any of the larger sources, the reduce potential would decrease significantly. Therefore, there is a trade-off between influent water quality and reuse volumes. In this study, maximising the reuse potential was prioritised in order to increase the volume of water available for irrigation and thereby reduce the reliance on the municipal water supply. As a result, the treatment solution must be designed for the higher contaminant loads associated with the inclusion of all greywater sources.

Table 5.8: Estimated monthly irrigation demand and available water resources for the currently cultivated farming areas during wet and dry season conditions.

Area	Season	Greywater [L]	Well [L]	Rainy days	Irrigation need [L]
Area I	Wet season	25797	30000	14.2	51298
Area I	Dry season	25797	30000	0.8	95044
Area III	Wet season	13533	-	14.2	43293
Area III	Dry season	13533	-	0.8	80213

The irrigation demand is influenced by the greywater generation, additional water sources and amount of rainy days. In Area I, the shallow well (see Figure 3.3) is currently used for irrigation and can provide water for around 500 m^2 of cultivated land. The proposed greywater treatment system is intended to operate together with the well in order to reduce the reliance on municipal water supply as much as possible.

Furthermore, on rainy days, no additional irrigation is needed. Therefore, the irrigation need has been divided into the wet- and dry season. Based on Table 3.1, the average number of rainy days per month was derived and accounts for the decrease in irrigation need during the wet season. This represents an average value used in the calculations. In reality, rainfall is higher during the peak rainy season and gradually decreases closer to the dry season.

However, greywater generation may also vary seasonally due to differences in water availability and water use practices. Water outages are more common during the dry season, which could reduce the water consumption and consequently the greywater generation. However, this does not necessarily stop greywater generation completely, since alternative water sources, such as bottled water, are then used. Therefore, greywater is assumed to be consistently generated throughout the year.

As shown in Table 5.8, the irrigation demand during the dry season is considerably higher than during the wet season. At the same time, greywater is generated at a relatively constant rate throughout the year and is insufficient to meet the irrigation demand on its own. Consequently, it is not possible to maintain the same cultivation area during the dry season as during the wet season. For this reason, the comparison is based on the farmland that is actually cultivated during each season, rather than assuming that the wet-season cultivation area can be maintained throughout the year.

Table 5.9 displays the current cultivation area, representing the farmland in use during the wet and dry seasons. This cultivation is irrigated through rainfall, the shallow well, and municipal water. The potential cultivation area in Table 5.9, on the other hand, represents the land that could be cultivated if rainfall, the shallow well, and treated greywater were utilized for irrigation.

For Area I during the wet season, the potential cultivation area of 1722 m^2 exceeds the actual cultivated area. Therefore, it would be possible to increase cultivation in Area I during the wet season while completely eliminating the need for municipal water for irrigation.

In Area III during the wet season, the potential cultivation is 894 m^2 which is less than the current cultivation. However, most of the land in Area III consist of maize fields. Maize is primarily grown during the wet season due to its high water demand and large required area. During the field studies, no manual irrigation of maize was observed as rainfall provided sufficient water. Consequently, the potential cultivation area should not be directly compared with the current cultivated area. Instead, the reused greywater could be used to support additional cultivation beyond the maize fields. It represents an additional water source that can be used for crops that require supplementary irrigation.

Table 5.9: Current cultivation and potential cultivation during the wet and dry season for Area I and Area III.

Scenario	Current cultivation [m^2]	Potential cultivation [m^2]
Area I – Wet season	1647	1722
Area I – Dry season	1500	993
Area III – Wet season	1390*	894
Area III – Dry season	0	280
Combined dry-season operation	1500	1273

*Mainly rain-fed maize cultivation which do not require manual irrigation.

In the dry season, the potential cultivation is less than the actual cultivation in both Area I and Area III, indicating that a smaller cultivation area could be maintained without relying on the municipal water supply. During the dry season, no farming activities are currently conducted near Area III, although with continued greywater generation in the area. Based on the estimated irrigation demand, approximately 280 m^2 could be cultivated in Area III using reclaimed greywater (Table 5.9). In Area I, approximately 993 m^2 could be cultivated using both reclaimed greywater and water from the shallow well (Table 5.9).

However, when compared to the current farming areas cultivated during the dry season (farming lands 3 and 4 in Figure 5.19), a combined operational strategy could be more suitable for the proposed treatment solution (see Table 5.9). The total irrigated area (Area I + Area III) achievable without municipal water is smaller than the current dry season cultivation area of approximately 1500 m^2. However, greywater reuse could reduce the reliance on municipal water supply by about 85% when comparing the potential cultivation to the current cultivation. Depending on priorities in the dry season, reused greywater could be used to increase food production together with municipal water. Another approach is to maintain a similar cultivation area while significantly decreasing municipal water consumption.

As the school continues to expand with additional students, larger volumes of greywater will also be generated. This enables additional irrigation capacity as the school grows. Based on the estimated greywater generation per student (Table 5.2) and the calculated irrigation demand per square metre of 2 L/m^2/d, approximately 5 m^2 of additional cultivated land could be irrigated for each additional student. Using the same estimation, the greywater generated from one additional staff member could potentially irrigate approximately 35 m^2 of additional cultivated land. However, these estimations are simplified and only based on the estimated water demand and greywater generation, without considering factors such as seasonal variability and rainfall. Nevertheless, the estimation highlights that the irrigation capacity is expected to increase as the school continues to expand.

5.6.2 Assumed influent quality

Since all selected greywater sources were intended to be included in the proposed treatment system, the influent greywater entering the treatment chain was assumed to consist of a mixture of the different greywater streams.

Table 5.10 presents the estimated influent greywater quality after mass balance calculations for turbidity, electrical conductivity (EC), and estimated *E. coli* concentrations. Nitrate concentrations were assumed to be 0 mg/L in the influent greywater for both Area I and Area III, since the measured nitrate concentrations were generally low throughout the study.

Table 5.10: Estimated influent greywater qualities for Area I and Area III based on simplified mass balance calculations and estimated parameter ranges.

Parameter	Area I	Area III
Turbidity [FNU]	562	418
EC [μS/cm]	1435	566
E. coli [CFU/100 mL]	2.00×10^6	1.89×10^6
Nitrate [mg/L]	0	0
pH [-]	7.17–9.15	7.19–7.97
BOD/COD [-]	<0.3	0.3–0.5
Temperature [°C]	23.19–25.4	23.19–25.4

For pH and the BOD/COD ratio, ranges were instead estimated based on the lowest and highest values reported for these parameters in Section 5.3. The ranges are presented in Table 5.10. This approach was selected since direct mass balance calculations were not considered suitable for these parameters. However, it is important to note that these ranges should only be interpreted as simplified estimates and may not fully represent the actual variation in the combined greywater quality if measured directly in situ.

Finally, the measured greywater temperature from all greywater sources at Tumaini Open School varied between 23.19–25.4 °C. This range was therefore also assumed to represent the expected temperature range of the combined influent greywater for both Area I and Area III, as presented in Table 5.10.

5.6.3 Collection of the greywater

Currently, greywater is discharged directly into the environment, as described in Section 5.1. The proposed solution must enable the collection and conveyance of greywater to the treatment system.

In Area I, this includes connecting the outlet pipes from the sanitary block to an underground pipe system diverting the greywater towards the treatment system. Furthermore, a new laundry station is planned to be constructed close to Dormitory 2 as described in Section 3.1. It is therefore suggested that greywater collection pipes should be integrated during construction in order to divert the generated greywater from the laundry station to the septic tank. The dishwashing stations will also require greywater collection pipes connected to the treatment system.

It was noticed that only a few students utilize the basins for dishwashing, whereas most discharge the water directly on the ground. Since all generated greywater is needed in order to maximize the irrigation potential, additional collection capacity for dishwashing greywater is necessary. As no further dedicated dishwashing facilities are currently planned, and there is not enough space for multiple people to do dishes simultaneously, it is suggested that students use the designated laundry stations for dishwashing as well. By making the laundry station multi-purpose, students may also gain easier access to soap during dishwashing which was noticed to be excluded in most instances.

Another solution to collect dishwashing water is to emphasized to the students that it is important that all greywater is collected. Whether this occurs through forming dishwashing lines near the dining hall or by transporting the dishes to the laundry area is therefore of less importance, as all collected greywater will ultimately be conveyed to the septic tank.

In Area III, greywater is currently discharged into the drainage channel located behind the volunteers' house as seen in Figure 5.7. Therefore, it is suggested to investigate the feasibility of connecting the channel to the septic tank. Furthermore, the greywater from the utility building is currently discharged through drainage pipes, and could similarly to Area I, be collected through additional underground piping and conveyed to the septic tank.

5.6.4 Septic tank

The same treatment system, consisting of a septic tank and an intermittent sand filter (ISF), was selected for both Area I and Area III, with only minor differences in dimensions between the two designs. Therefore, the solution for Area I is discussed in detail, while the corresponding design for Area III is presented in Appendix D. Septic tanks were chosen as the pre-treatment prior to the ISF. The technology is suitable in the local context, since septic tanks are already commonly used for wastewater collection in the area. Therefore, the construction and operation of the system are expected to be more feasible compared to less familiar treatment technologies.

The septic tank is placed underground and should be made out of concrete with 10 cm thick walls. Although several construction materials may be suitable, concrete was selected since it is already commonly used for septic tanks in the area, making it appropriate for the local context.

The tank will collect the generated greywater and store it for approximately 24 h to allow larger particles to settle. It will also even out the irregular greywater generation and allow dosing of a constant volume onto the ISF.

A vertical section of the dimensioned septic tank is shown in Figure 5.20. The total tank volume was slightly above 4 m^3, with dimensions of 2.8 m $\times$ 1.2 m $\times$ 1.2 m (length $\times$ width $\times$ height). The tank volume provides storage for the inflow of greywater,

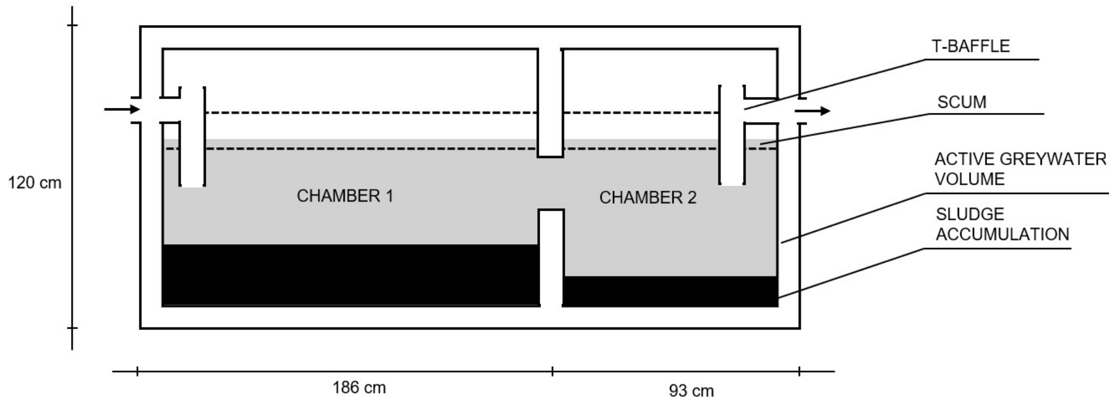


Figure 5.20: Vertical section of septic tank in Area I.

buffering of peak flows, and sludge accumulation. The second chamber was designed to be half the length of the first chamber, which had a length of 186 cm.

Both the inlet and outlet will consist of T-baffles, where 10 cm extends above the liquid surface to allow ventilation, while 25 cm extends below the liquid surface to minimize turbulence from the incoming flow (US EPA, 1980). The baffles are designed to reduce short-circuiting and promote sedimentation within the tank. Manholes should be located on top of the tank above the inlet and outlet in order to facilitate inspection, cleaning, and maintenance.

The tank will operate with an average HRT of 24 hours as it has been reported that extended storage should be avoided and it is sufficient for sedimentation of particles(Dixon et al., 2000). The settling and storage time will be achieved operationally by collecting and storing greywater during the first day of operation. The following day, the water is intermittently fed onto the filter. This strategy results in varying storage times, where greywater generated early during the day will be stored for up to approximately 36 h, while greywater generated later during the day may be stored for approximately 12 h before dosing.

The volume of the tank was partly based on the emptying interval of the sludge. However, as many studies reported emptying intervals for septic tanks with general wastewater, the required interval for greywater septic tanks remains uncertain. Therefore, a conservative emptying interval of once per year was assumed, in order to estimate the annual sludge production. Septic tanks for general wastewater suggest a sludge accumulation rate of 40–90 L/pers/yr (Norris, 2000), whereas greywater sludge accumulation has been reported to range from 18–20 L/pers/yr (Mohamed, 2011). Greywater will therefore likely produce less sludge compared to general wastewater and it will be possible to empty the tank less frequent. However, this can be adjusted after a period of operation once the actual sludge accumulation at the study site has been evaluated.

The treatment performance of the septic tank is uncertain since only greywater is collected. Septic tanks rely on both sedimentation and anaerobic biological processes, where microorganisms are naturally introduced through the wastewater. General wastewater introduce microbes through faecal matter, which is absent in greywater. Therefore, the biological degradation in the tank is uncertain, and could likely be less effective compared to traditional septic tanks. Furthermore, the estimated BOD/COD ratio, as seen in Table 5.10, indicated relatively low biodegradability which may further limit the biological processes in the tank. Nevertheless, sedimentation of larger particles and separation of floating materials are still expected to occur, thereby reducing the contaminant load before further treatment in the intermittent sand filter.

Future expansion of the school was considered in the design of the septic tank. The sludge storage volume was estimated for a larger population than the current number of students at the school. Furthermore, the active liquid volume was dimensioned based on the maximum estimated greywater flow, including a safety factor and additional storage capacity. Therefore, the septic tank is expected to be able to accommodate moderately increased greywater flows in the future.

However, long-term, additional storage capacity will be required as the school continues to expand. It remains uncertain when such expansion would become necessary and whether a new ISF would also be required, or if an additional septic tank could be connected to the existing ISF.

5.6.5 Intermittent sand filter

Previous studies comparing continuously and intermittently loaded filters have shown that intermittent loading reduces the extent of clogging, thereby reducing the required sand to be replaced during maintenance (Grace et al., 2016). Since the study area is located in a rural environment, low maintenance requirements were preferred due to limited access to technical expertise and specialized equipment. Therefore, an intermittent sand filter (ISF) was dimensioned as the second part of the treatment system.

The vertical section of the intermittent sand filter in Area I can be seen in Figure 5.21, with the top view displayed in Figure 5.22. Although the filter could be partly buried underground, above ground simplifies maintenance activities and is therefore selected. The top of the filter consists of a cover, located 50 cm above the filter surface. The space allows ventilation from the underdrain and reduces odours (US EPA, 1980). The cover could be made out of either treated wood or metal.

The sand layer acts as the primary treatment layer in the ISF. It has a depth of 90 cm with an effective grain size (d_{10}) of 0.5 mm and a uniformity coefficient below 4.0. The bed depth was selected in the upper range of the recommended design criteria due to the elevated turbidity levels and overall poor quality of the influent greywater (Table 5.10). The prototype filter media had a grain size ranging from 0.8–2 mm, which is substantially larger than the recommended maximum grain size of 1.5 mm for intermittent sand filters (US EPA, 1980). Despite the larger grain fractions, the prototype achieved turbidity removal efficiencies of approximately 87.9%. With a smaller sand fraction, even higher removal efficiencies are expected.

The influent water quality includes all measured greywater sources at Tumaini Open School. However, as previously mentioned, the student shower water was likely more turbid due to the accumulation of greywater in the collection bucket, which influenced the combined influent water quality presented in Table 5.10. Nevertheless, the greywater sources at the school were generally more contaminated than those reported in the literature, supporting the need for a greater sand filter depth, even if some of the measured values may have been overestimated.

Underneath the sand layer, a 10 cm layer of pea gravel with a grain size ranging from

0.6–1 mm is located. The layer acts as a transition between the sand filtration layer and the underlying drainage layer. A similar configuration was tested in the prototype in order to prevent smaller particles from being washed out and clog the drainage layers. A slightly greater depth of pea gravel was selected compared to the design criteria as a safety margin.

The final drainage layer consists of a 30 cm thick gravel layer with a grain size ranging from 2–4 mm. Within the drainage layer, a perforated underdrain pipe (d = 100 mm) sloped at 0.7% collects the filtered greywater. According to the design criteria, only one underdrain pipe was required, and a vertical ventilation pipe is located upstream the underdrain. Similarly to the transition layer, a greater depth was selected as a safety margin compared to the design criteria.

The selected filter configuration was based on an optimal HLR of 200 $L/m^2/d$, with a resulting filter area of 5.8 m^2. Four doses per day were selected to enable a sufficient dose depth of 0.05 m to sufficiently flood the filter. The volume of each dose was based on the design flow of 1160 L/day and correspond to 290 L/dose.

Different configurations were iteratively evaluated, including higher HLRs than recommended in the design criteria for general wastewater treatment systems (US EPA, 1980). However, since the greywater at the school was found to be of poorer quality compared to values reported in literature, a more conservative HLR was selected in accordance with the design criteria. By selecting a lower HLR, the risk of clogging and maintenance requirements may be reduced compared to a higher HLR.

Furthermore, a study conducted by Sabbah et al., 2004, found that 5–10 doses was optimal for filter performance. However, by increasing the amount of doses, it was not possible to sufficiently flood the filter in accordance to the criteria in the design manual (US EPA, 1980). Since two doses per day represented the minimum dosing frequency, four doses per day were considered sufficient.

The doses were distributed evenly every six hours throughout the day, according to Table 5.11. The dosing times were selected to correspond to the major greywater generation peaks identified in the weekly profile (Section 5.2). Thus, the morning dose captures greywater generated during the the early morning whereas the last dose will capture the second peak of the day.

Table 5.11: Selected dosing times and corresponding time periods.

Dose time	Time period
07.00	Before breakfast
13.00	Between breakfast and lunch
19.00	Between lunch and dinner
01.00	Night

During each dose of greywater, the influent enter the main distribution pipe (d=50 mm), according to the black arrow pointing towards the filter in both figures. The water is then distributed into the six lateral pipes (d=30 mm) across the filter surface, spaced 36 cm apart. The lateral pipes contain 4 mm diameter orifices every 30 cm. In total 32 orifices are placed across the lateral pipes, with a total length of 11.84 m (2 x 1.02 m, 2 x 2.26 m, and 2 x 2.64 m) as seen in Figure 5.22. The main distribution pipe does not contain any orifices to decrease the head loss and instead primarily works as a distribution pipe. A pump must provide a head of 91–183 cm at each orifice (U.S. EPA, 1999).

After each dose, air re-enters the filter which enables aerobic decomposition of the greywater (U.S. EPA, 1999), therefore, sufficient time between doses is important. Furthermore, microbial activity usually occur in a sand filter, where temperature is one of the most important factors. Such filters have been reported to perform more efficiently in warmer climates, making the study site particularly favourable.

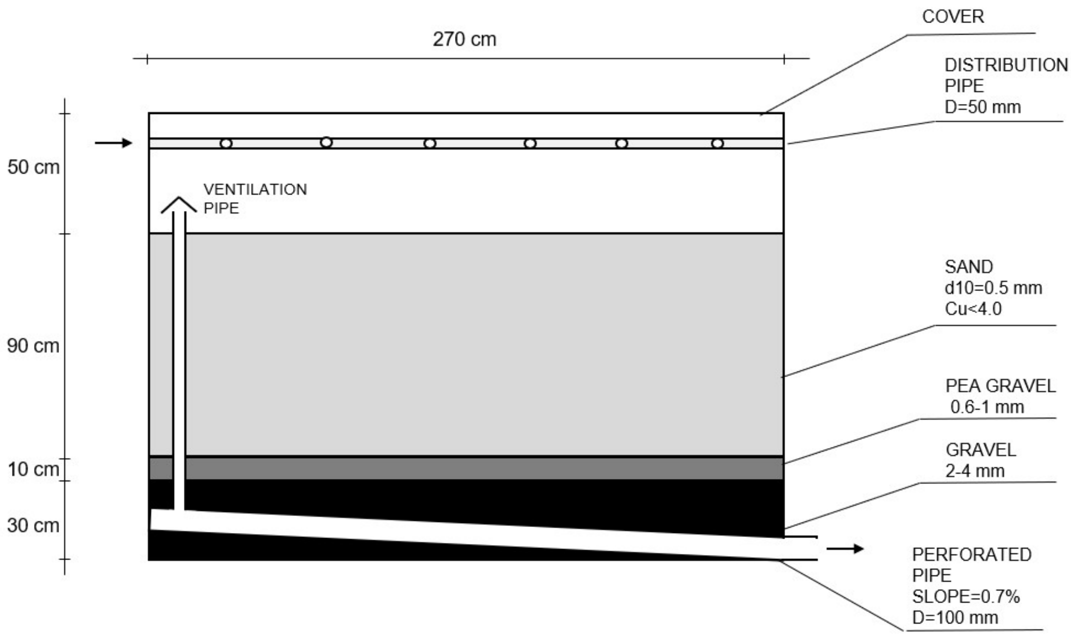


Figure 5.21: Vertical section of intermittent sand filter in Area I.

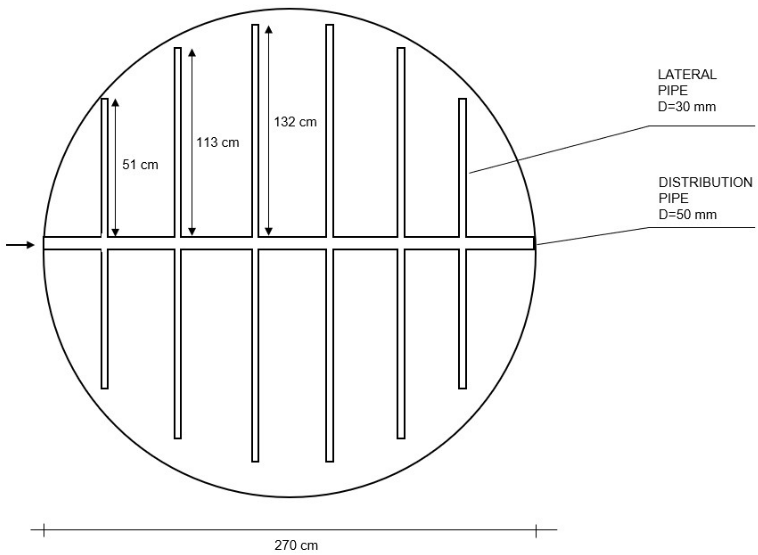


Figure 5.22: Top view of the distribution filter in the intermittent sand filter.

An intermittent sand filter was considered the most suitable treatment solution for the local context. Constructed wetlands (CWs) were also evaluated as a potential treatment alternative. However, due to the intense rainfall during the rainy season, there is a risk that the wetland system could become saturated, which potentially could reduce the treatment efficiency. Furthermore, CWs rely on biological treatment processes to a great extent. The relatively low BOD/COD ratio estimated in the greywater suggests lower biodegradability, which will limit the effectiveness of CWs. In comparison, ISF rely to a greater extent on physical filtration which makes them more suitable in the local context. Furthermore, sand is easily accessible in the area, although, the availability of sand within the recommended grain size range still needs to be evaluated.

The filter was dimensioned to accommodate some future expansion of the school, as a safety factor was included in the design to account for increased greywater flows. However, the long-term capacity of the system remains uncertain, and additional treatment units may eventually be required to ensure efficient treatment of all generated greywater.

From a shorter perspective, it is suggested to instead adapt the operation of the existing filter system by modifying the dosing scheme and increasing the hydraulic loading rate (HLR). The selected design already applies the maximum recommended HLR for ISFs treating general wastewater. However, since greywater generally contains lower concentrations of solids compared to general wastewater, the risk of clogging is lower. Consequently, the filter may potentially operate at higher flow rates without requiring an increased filter area. Such an operational adjustment could extend the usability of the system before additional treatment is needed. However, operating at higher HLRs may increase the maintenance requirements and lead to more frequent replacement of the filter media due to clogging. Nevertheless, replacing the filter media is likely more cost-effective than constructing an entirely new treatment system.

5.6.6 Storage and distribution system

After treatment through the intermittent sand filter (ISF), the water is then transported through a pipe system to an elevated storage tank. No exact pipe dimensions between the ISF and the storage tank were determined within the scope of this project. A pump is required to transport the treated greywater from the outlet, located close to ground level, to the elevated storage tank. The selected pump should be capable of providing sufficient head to covey the treated greywater to the storage tank. Furthermore, a solar powered pump is proposed to avoid reliance on the external electricity supply.

The storage tank volume was dimensioned to temporarily store up to three days of treated greywater production. Appendix D.3 presents the required storage volume for Area III. For Area I, the required storage volume was calculated to approximately 2580 L (2.58 m^3) based on the weekly greywater generation of 6019.30 L/week. However, the final tank size should preferably be selected based on locally available standard dimensions. As an example, 5 m^3 elevated plastic tanks are already in use at Tumaini Open School for municipal water, as shown in Figure 5.23. A similar tank configuration is therefore considered suitable for the proposed system. Plastic tanks were also considered appropriate due to their relatively low weight, ease of installation, and local availability.

However, it is important that treated greywater is not stored for unnecessarily long periods, as prolonged storage may result in microbial regrowth and deterioration of water quality (World Health Organization, 2006a). Consequently, the storage tank was intended primarily for short-term balancing and temporary storage of treated greywater rather than long-term retention. No exact dimensions of the tank were determined

Figure 5.23: Existing municipal water storage tank at Tumaini Open School (5 m^3).

within the scope of this project, only the required storage volume.

A tap outlet should be installed at the storage tank to allow students and staff at the school to manually collect treated greywater. The elevated storage tank was also selected to support the possible future implementation of a gravity-driven drip irrigation system. By elevating the storage tank, the hydraulic head generated by the water level in the tank should enable distribution of treated greywater in a drip irrigation system without additional pumping requirements.

A study conducted in Nigeria by Isikwue et al. (2016) implemented a small-scale gravity-driven drip irrigation system using a 2000 L plastic tank elevated 2.8 m above ground level in order to achieve the minimum required pressure. The system successfully irrigated approximately 900 m^2 of agricultural land without additional pumping requirements. Based on these findings, a similar tank elevation could be selected at Tumaini Open School. However, further hydraulic investigation would be required to ensure that sufficient pressure can be achieved under the site-specific conditions.

The storage tank should also be designed with an overflow system allowing excess treated greywater to be discharged during periods when the treated water production exceeds the irrigation demand, such as during the wet season. The excess water could either be discharged directly onto the ground or, preferably, transported through a hose or a pipe system to a designated disposal area.

5.6.7 Operation and maintenance

Based on the findings from the social acceptance survey on greywater reuse (Appendix B.2), trust in the system was closely connected to information on how to use the it and adequate training prior to implementation. Respondents expressing higher trust in the treatment system also tended to report greater willingness to reuse treated greywater for irrigation. Therefore, operation and maintenance of the proposed treatment system are considered important not only from a technical perspective, but also for achieving long-term acceptance and successful implementation of greywater reuse at Tumaini Open School. In the following section, operation and maintenance practices are therefore described.

Firstly, it is important to establish a clear structure regarding who is responsible for the different operation and maintenance tasks required for the system (Environmental Protection Agency, 1999). All involved individuals should be well informed about the purpose of the treatment system, how it functions, and the potential risks associated with greywater reuse. In the social acceptance survey, the results revealed that both the teachers and students were willing to help operate and maintain the treatment system. In the proposed approach, teachers are suggested to receive initial training and take a primary responsibility for the operation and management of the system, while students should also be informed and educated about the system through the teachers.

Both septic tanks and ISFs generally require relatively low operation and maintenance when properly designed (US EPA, 1980). The accumulation of scum and sludge in the septic tank should initially be inspected approximately once per year. However, once the site-specific accumulation rates at the school have been established through operation, the inspection interval can be adjusted accordingly.

The thickness of the scum layer can be estimated by carefully lowering a stick or similar tool through the floating layer until resistance from the bottom of the scum is detected (US EPA, 1980). If the distance between the bottom of the scum layer and the bottom of the outlet pipe becomes less than approximately 8 cm, the tank should be cleaned.

The sludge depth can be estimated by lowering a stick wrapped in a light-colored cloth to the bottom of the tank and then observing the height of sludge particles attached to the cloth after it has remained in the tank for a few minutes (US EPA, 1980). If the distance between the top of the sludge layer and the bottom of the outlet pipe becomes less than approximately 20 cm, the tank should be cleaned.

The septic tank can be emptied by lowering a smaller portable pump through the manhole and disposing of the greywater and sludge at an appropriate disposal location. However, since the school already has five septic tanks, it is proposed that the greywater septic tanks are emptied simultaneously when one of the existing septic tanks at the school requires emptying. During these occasions, a specialized vacuum truck is typically used to pump, transport, and dispose of the tank contents.

Once the septic tank has been emptied, it can be cleaned using only water or small amounts of ordinary detergents, soap, or bleach if needed (US EPA, 1980). However, complete cleaning of the tank is not necessarily required after emptying, as the system can continue operating directly after sludge removal and refilling with new greywater. After each emptying and cleaning event, the inlet and outlet structures should also be inspected to ensure that the pipes, baffles, and other system components remain intact and function properly.

For the ISF, it is important to frequently monitor both the influent and effluent greywater quality during the initial stages of operation. The sand filter requires a maturation period before reaching stable treatment performance, which may vary from approximately two days up to two weeks (US EPA, 1980). During this maturation period, the achieved removal efficiencies for different water quality parameters may be significantly lower compared to those of a fully matured filter. Consequently, the treated greywater might initially not fulfil the required effluent quality criteria for irrigation reuse. In such cases, it is recommended that the treated greywater is temporarily discharged at an appropriate disposal location, preferably at a safe distance from living areas at the school. Continued monitoring should then be carried out until the treatment efficiencies stabilize, indicating that the filter has matured and reached more stable operating conditions.

Once the filter has matured, it remains important to regularly perform observations and measurements to evaluate whether the system is functioning properly (World Health Organization, 2006a). For Tumaini Open School, it is recommended that the operational monitoring should, to the greatest extent possible, avoid reliance on advanced and costly laboratory equipment. Instead, the main focus should be on simple operational monitoring and regular visual inspections. For example, observations of whether the flow through the filter appears normal can provide important indications of system performance, while reduced flow may indicate that clogging has occurred within the filter.

Although the maintenance procedures should remain as simple and practical as possible, it is still essential that the health and safety of the staff and students at the school are prioritized. Therefore, regular monitoring should be carried out to ensure that the treated greywater complies with the relevant guideline values for irrigation reuse discussed in Section 2.3.3. To document the measurements and monitor how the water quality changes over time, it is recommended that a sample analysis report form is used. In addition, relevant equipment for measuring selected water quality parameters should either be available directly at the school in the future laboratory or be accessible through lending from nearby laboratories (Environmental Protection Agency, 1999).

Clogging is one of the main operational challenges associated with ISFs, particularly when the influent greywater contains high concentrations of suspended solids, grease, or organic material (Assayed et al., 2010; Environmental Protection Agency, 1999). Excessive biofilm growth and particle accumulation within the sand pores may gradually reduce the infiltration capacity of the filter. Signs of clogging can therefore be detected through regular visual inspections, for example by observing whether the greywater drains more slowly than normal, if ponding water appears on the filter surface, or if the dosing frequency no longer matches the infiltration capacity of the filter (US EPA, 1980; World Health Organization, 2006a).

If clogging has occurred, the filter can temporarily be taken out of operation to allow the biological layer to stabilize and partially recover (US EPA, 1980). If necessary, accumulated material at the top of the filter surface can also be removed by scraping or replacing the upper sand layer. In the study by Sabbah et al. (2004), the upper 30–40 cm of sand was removed and replaced after clogging had occurred in the ISF. Similarly, Assayed et al. (2010) reported clogging within the upper 50 cm of a 60 cm sand layer. These findings highlight that the extent and development of clogging may vary considerably between systems depending on site-specific conditions. Therefore, it is important that the operation and maintenance routines at Tumaini Open School are adapted over time based on the observed performance of the system under local conditions.

As the school continues to grow according to the planned future expansion, the proposed treatment systems are still expected to remain functional to a certain extent, since safety factors and additional treatment capacity were incorporated into the design. Consequently, the systems are expected to be capable of handling moderately increased greywater flows compared to the current situation. In addition, the hydraulic loading rate (HLR) could potentially be increased in the future in order to enable treatment of larger greywater volumes within the existing filter area. However, such operational adjustments would require continued monitoring to ensure that the treated greywater still complies with the relevant guideline values for irrigation reuse.

Nevertheless, as the school population and greywater generation continue to increase over time, a point will eventually be reached where the proposed treatment systems will no longer be capable of adequately treating all generated greywater. At that stage, it is suggested that additional separate treatment systems are constructed based on principles and designs similar to those proposed in the present study.

5.7 Quantitative Microbial Risk Assessment

To further evaluate the proposed treatment solution from a health risk perspective, a Quantitative Microbial Risk Assessment (QMRA) was conducted for the selected treatment system and reuse scenarios. Since no site-specific microbiological analyses or measurements of pathogen removal were conducted, pathogen concentrations and treatment performance values were obtained from literature. Consequently, the QMRA should be regarded as an indicative assessment of potential health risks rather than a direct validation of the proposed system under site-specific conditions.

The site-specific input parameters were set as stated in the method chapter (Table 4.8). The evaluated pathogen was *E. coli*, with estimated concentrations of 2.00×10^6 CFU/100 mL in Area I and 1.89×10^6 CFU/100 mL in Area III, from Table 5.10. Since Area I exhibited the highest estimated *E. coli* concentration, all of the subsequent QMRA sensitivity analyses were performed for Area I in order to represent the more conservative and worst-case exposure conditions.

The DALY and annual infection risk results should therefore be interpreted specifically in relation to *E. coli* as a bacterial indicator organism. This means that the results do not fully represent all pathogen groups relevant for greywater reuse, particularly viruses and protozoa, which may require higher treatment reductions (World Health Organization, 2006c).

The treatment barriers included in the QMRA assessment for the proposed final solution were a septic tank followed by ISF. The LRV for the septic tank was conservatively set to 0.5, in accordance with the pre-defined input data used in the QMRA tool (Knutsson, 2026). This value is based on reported pathogen removal in greywater septic tanks according to World Health Organization, 2006a. The relatively low pathogen reduction is primarily attributed to the limited removal of suspended particles and particle-associated microorganisms in sedimentation-based treatment processes.

For sand filtration, a LRV of 3 was assumed for bacterial reduction. This value was based on reported performance values for rapid sand filtration from WHO, which state that sand filters with fine- to medium-grained media can achieve reductions of more than 3 log units for indicator bacteria (World Health Organization, 2006a). However, the proposed treatment system in this study consists of an ISF rather than a rapid sand filter. Consequently, the assumed LRV may overestimate the actual bacterial removal performance. For example, a study investigating intermittently fed slow sand filters reported an average *E. coli* removal of 1.77 ± 0.68 log units, although maximum removals of up to 3.23 log units were observed under favourable conditions (Lubarsky et al., 2022). Therefore, while a 3-log reduction is achievable, it may not be consistently attained in practice and should be considered a source of uncertainty in the QMRA results.

The results from the QMRA are summarized in Table 5.12 and Table 5.13. The evaluated exposure scenarios for greywater reuse included *Garden irrigation (operator)*, *Raw vegetable consumption*, and *Cooked vegetable consumption*. For each scenario, both the disease burden, expressed as DALY per person per year (pppy) and compared to the WHO reference value of 10^{-6} DALY pppy, and the annual infection risk, compared to the WHO reference value of 10^{-4} infections pppy, were evaluated.

The DALY results for *E. coli* in Area I and Area III are presented in Table 5.12. As shown in the table, all evaluated scenarios resulted in both median and 95th percentile DALY values below the WHO guideline value of 10^{-6} DALY pppy. Based on the pathogen concentrations and treatment performances assumed in the QMRA, this suggests that the estimated disease burden associated with the proposed greywater reuse system is within the acceptable level defined by WHO. In practical terms, the results indicate that the severity of illness associated with the evaluated exposure pathways is expected to remain low, even under the more conservative conditions represented by the 95th percentile values. However, the results should be interpreted as indicative, since the assessment relied on literature-based pathogen concentrations and assumed treatment efficiencies rather than site-specific microbiological measurements.

Table 5.12: Summary of DALY results for the evaluated exposure scenarios based on *E. coli*. Median and 95th percentile values are presented for Area I and Area III.

	Median DALY pppy		**95th percentile**	
Exposure scenario	**Area I**	**Area III**	**Area I**	**Area III**
Garden irrigation (operator)	8.21×10^{-10}	7.76×10^{-10}	2.06×10^{-8}	1.95×10^{-8}
Raw vegetable consumption	2.31×10^{-8}	2.18×10^{-8}	5.77×10^{-7}	5.46×10^{-7}
Cooked vegetable consumption	1.62×10^{-8}	1.53×10^{-8}	4.06×10^{-7}	3.83×10^{-7}

However, when evaluating the QMRA results for annual infection risk presented in Table 5.13, it can be seen that most of the evaluated values exceed the WHO reference of 10^{-4} infections pppy. The values exceeding the reference level are marked with bold text in the table. Only the median annual infection risk for garden irrigation in Area I and Area III remained below the recommended WHO limit. This indicates that although the overall disease burden expressed as DALY remained within the acceptable WHO target, the probability of infection may still be significant for certain exposure pathways. The results therefore suggest that additional treatment barriers or other risk reduction measures may be required to further decrease the infection risks associated with treated greywater reuse. This is particularly important for irrigation of crops intended to be consumed raw, as this exposure scenario resulted in the highest estimated infection risks among the evaluated cases.

Table 5.13: Summary of annual infection risk results for the evaluated exposure scenarios based on *E. coli*. Median and 95th percentile values are presented for Area I and Area III. Values exceeding the WHO reference value of 10^{-4} infections pppy are shown in bold.

	Median annual infection risk		95th percentile	
Exposure scenario	**Area I**	**Area III**	**Area I**	**Area III**
Garden irrigation (operator)	8.21×10^{-6}	7.76×10^{-6}	$\mathbf{2.06 \times 10^{-4}}$	$\mathbf{1.95 \times 10^{-4}}$
Raw vegetable consumption	$\mathbf{2.31 \times 10^{-4}}$	$\mathbf{2.18 \times 10^{-4}}$	$\mathbf{5.77 \times 10^{-3}}$	$\mathbf{5.46 \times 10^{-3}}$
Cooked vegetable consumption	$\mathbf{1.62 \times 10^{-4}}$	$\mathbf{1.53 \times 10^{-4}}$	$\mathbf{4.06 \times 10^{-3}}$	$\mathbf{3.83 \times 10^{-3}}$

5.7.1 Sensitivity of results

The QMRA results should be interpreted as indicative rather than as exact predictions of the health risks associated with the proposed treatment system. The primary purpose of the model is to evaluate whether the selected treatment system appears sufficient from a health risk perspective, or if additional treatment barriers and risk reduction measures may be required. Several assumptions within the QMRA tool are intentionally conservative, which can contribute to an overestimation of the actual risks associated with the evaluated reuse scenarios.

One example is the exposure scenario *Vegetable consumption (cooked)*. In the QMRA model, cooking is represented only by assuming a smaller amount of residual treated greywater remaining on the vegetables prior to consumption, while no thermal inactivation of pathogens during cooking is included in the calculations (Knutsson, 2026). In reality, WHO reports that cooking can provide pathogen reductions of up to 5–6 log units prior to consumption (World Health Organization, 2006c).

To evaluate the influence of thermal inactivation during cooking, an additional scenario including an extra 5-log pathogen reduction was tested. The results showed a substantial decrease in annual infection risk, as illustrated in Figure 5.24. In the figure, the upper graph presents the baseline scenario without thermal pathogen reduction during cooking, while the lower graph presents the scenario including an additional 5-log reduction. In the baseline scenario, both the median and the 95th percentile annual infection risks exceeded the WHO reference. However, when including the additional 5-log reduction, the estimated risks decreased substantially, with both the median and the 95th percentile remaining well below the WHO guideline value. The comparison clearly demonstrates that pathogen inactivation during cooking has a major influence on the estimated health risks associated with cooked vegetable consumption.

Furthermore, a complete failure scenario was tested, in which both the septic tank and sand filtration were assumed to provide 0% pathogen removal. When thermal inactivation during cooking was included, the 95th percentile values for both annual infection risk and DALY still remained below the WHO reference limits for the cooked vegetable scenario. Due to the strong influence of cooking-related pathogen inactivation, the *Vegetable consumption (cooked)* scenario was excluded from the following QMRA

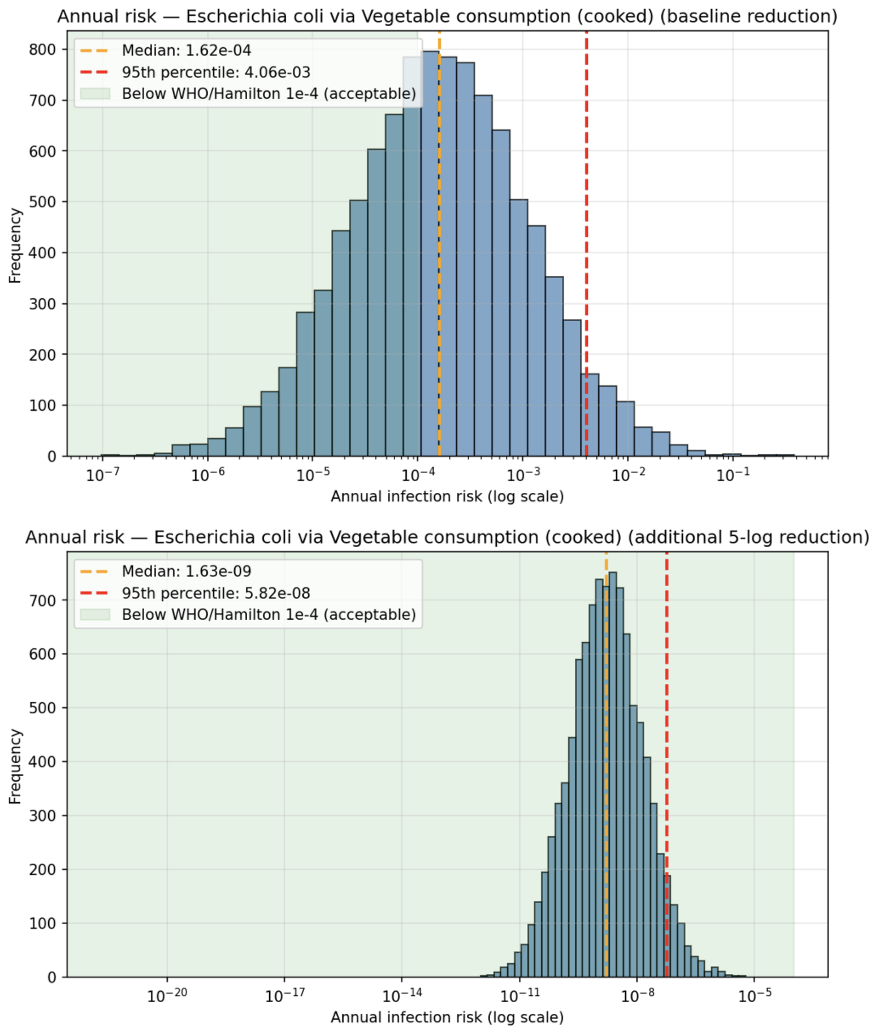


Figure 5.24: Comparison of annual infection risk distributions for the *Vegetable consumption (cooked)* scenario with and without thermal pathogen reduction during cooking. The upper plot shows the original QMRA scenario in which no thermal inactivation during cooking was included and the lower plot illustrates the effect of including pathogen reduction during cooking of 5 log units.

analyses.

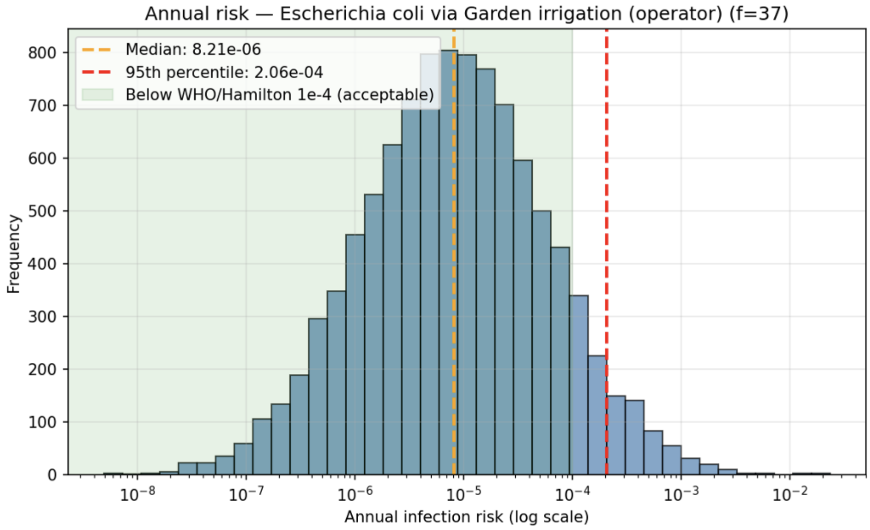
Another important assumption is the exposure frequencies defined in the QMRA input data. For the vegetable consumption scenarios, the selected exposure frequencies were based on repeated ingestion of small amounts of treated greywater through food consumption. However, for the *Garden irrigation (operator)* scenario, a conservative worst-case assumption was used in which accidental ingestion through hand-to-mouth contact was assumed to occur every time manual irrigation was performed, corresponding to approximately 37 exposure events pppy. In practice, this assumption may overestimate the actual exposure frequency, particularly if operators are aware of the potential health risks and apply basic hygiene measures during irrigation activities. It may therefore be more realistic to assume that accidental ingestion only occurs occasionally rather than during every irrigation event.

To evaluate the influence of this assumption, an additional sensitivity test was performed for Area I in which the exposure frequency for garden irrigation was reduced from 37 to 3 events per year. The resulting annual infection risk distributions are presented in Figure 5.25, where the upper graph represents the conservative worst-case assumption of 37 exposure events pppy and the lower graph represents the reduced exposure frequency of 3 events pppy. The comparison shows that the estimated infection risks decrease substantially when a lower and potentially more realistic exposure frequency is assumed. Under the conservative assumption of 37 exposure events pppy, the 95th percentile annual infection risk exceeded the WHO reference value of 10^{-4} infections pppy. However, when the exposure frequency was reduced to 3 events pppy, the 95th percentile risk remained below the WHO guideline value. This illustrates that the estimated infection risks are highly sensitive to assumptions regarding operator exposure frequency. In the subsequent analyses, the frequency of hand-to-mouth exposure was reduced to 3 events per year.

However, when evaluating degraded (25% efficiency) and complete failure scenarios for both the septic tank and the sand filter while using the reduced exposure frequency of 3 events pppy, the annual infection risk again exceeded the WHO reference value of 10^{-4} infections pppy. This indicates that although reducing the assumed frequency of hand-to-mouth contact significantly lowers the estimated risks during normal system operation, it does not eliminate the elevated risks that may occur during periods when the greywater treatment system is not functioning as intended. Therefore, the *Garden irrigation (operator)* exposure scenario was still included in the subsequent analyses but with the changed frequency of exposure ($f = 3$ events pppy).

To further evaluate the robustness of the proposed treatment system, additional QMRA analyses were performed under different treatment performance conditions. In these analyses, both degraded (25% efficiency) and complete failure (0% efficiency) conditions were simulated for the septic tank and sand filter. The results are summarized in Table 5.14, which presents whether the WHO reference value of 10^{-6} DALY pppy was met under the different treatment performance scenarios. The assessment was based on the median DALY values.

For the *Garden irrigation (operator)* exposure scenario, the WHO DALY target was met for all evaluated treatment performance conditions. This is mainly explained by the relatively low assumed exposure frequency for accidental hand-to-mouth ingestion during irrigation activities ($f = 3$ events pppy).



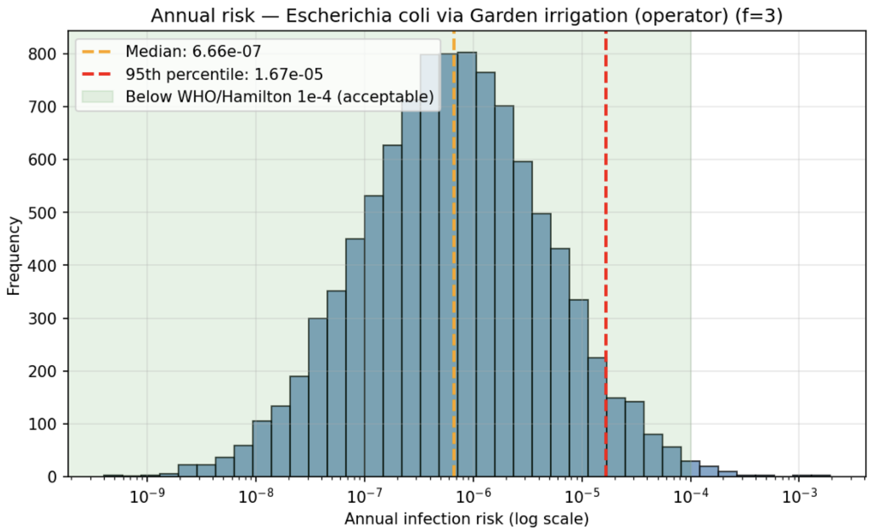


Figure 5.25: Comparison of annual infection risk distributions for the *Garden irrigation (operator)* scenario in Area I under two different exposure frequency assumptions. The upper plot shows the result for the conservative worst-case assumption of 37 exposure events per year, while the lower plot shows the result when the exposure frequency was reduced to 3 events per year.

Table 5.14: Evaluation of whether the WHO reference value for disease burden was met under different treatment performance scenarios for the septic tank and sand filter in Area I.

Septic tank	Sand filter	Garden irrigation	Raw vegetable consumption
Normal	Normal	Yes	Yes
Degraded	Normal	Yes	Yes
Normal	Degraded	Yes	No
Degraded	Degraded	Yes	No
Fail	Normal	Yes	Yes
Normal	Fail	Yes	No
Fail	Degraded	Yes	No
Degraded	Fail	Yes	No
Fail	Fail	Yes	No

For the *Raw vegetable consumption* scenario, the results show that the estimated disease burden is considerably more sensitive to disruptions in the treatment chain. Several degraded and failure scenarios exceeded the WHO DALY reference value, particularly when the sand filtration performance was reduced or completely lost. Since vegetables intended to be consumed raw are already cultivated at the school, these risks are considered important to account for in the evaluation of the proposed greywater reuse system. Therefore, the potential implementation of additional treatment barriers and risk reduction measures is further discussed in the following Section 5.7.2.

Another factor that strongly influences the estimated infection risks and DALY results is the selected log reduction values (LRVs) assigned to the treatment barriers in the QMRA tool. In this study, the LRVs were conservatively set to 0.5 log units for the septic tank and 3 log units for the sand filter based on values reported by World Health Organization, 2006a. However, it is important to acknowledge that these values are only estimates and that the actual pathogen reductions achieved under real operating conditions may differ substantially.

Even within the available literature, large variations in reported pathogen removal efficiencies can be observed. For example, Assayed et al. (2010) reported that the septic tank in their study achieved approximately 2.4 log units of *E. coli* reduction, which is considerably higher than the conservative 0.5 log reduction used as input in the QMRA model. At the same time, the opposite situation is also possible, where the selected LRVs may instead overestimate the actual treatment performance under certain operating conditions. This uncertainty is particularly relevant for the sand filtration step, where the assumed bacterial removal efficiency may vary depending on site-specific conditions and system operation. The QMRA results should therefore be interpreted with caution, since the estimated health risks are highly sensitive to the assumed treatment efficiencies of the individual treatment barriers.

5.7.2 Additional treatment barriers

Based on the results presented in Table 5.14, additional treatment barriers may be necessary to improve the robustness of the proposed greywater reuse system. Although several of the evaluated baseline scenarios fulfilled the WHO DALY target under normal operating conditions, future changes at the school may increase the overall health risks associated with greywater reuse. For example, the school plans to expand its capacity to accommodate up to approximately 450 students in the future, which could increase both greywater generation and pathogen loading within the treatment system.

To further evaluate the robustness of the proposed solution, several additional treatment and risk reduction barriers were therefore assessed using the QMRA tool. The evaluation focused on the *Garden irrigation* and *Raw vegetable consumption* exposure scenarios, since these were identified as the most relevant and sensitive pathways in the previous analyses. In these comparisons, the 95th percentile DALY values were used rather than the median values in order to account for uncertainties and potential future variations. Using the 95th percentile therefore represents a more conservative assessment of the long-term robustness of the proposed system.

One of the evaluated additional barriers was SODIS (solar water disinfection), which was assigned a bacterial reduction of 3 log units in the QMRA tool. This assumption was based on Eawag, 2002, which reported reductions of approximately 2–5 log units for *E. coli* after 6 hours of solar exposure. However, these reductions were achieved using traditional household-scale SODIS systems, typically involving PET bottles exposed to sunlight for drinking water treatment. If SODIS were to be implemented as part of the greywater treatment system at Tumaini Open School, it would likely need to operate at a substantially larger scale. One solution could be similar to the pyrex pipe system discussed in Section 2.2.2.5. Due to the uncertainty associated with the performance of large-scale SODIS systems for greywater treatment, a conservative 3-log reduction was selected for the QMRA comparison.

Another evaluated treatment barrier was biochar filtration. This was considered particularly relevant since the prototype filter evaluated at Tumaini Open School already included a layer of wood charcoal. Both biochar and wood charcoal are produced through pyrolysis under oxygen-limited conditions (Hagemann et al., 2018). However, biochar is typically engineered for environmental applications such as water treatment and often has a higher porosity and adsorption capacity, whereas wood charcoal is primarily produced as a fuel and is generally less effective for contaminant removal from water. In a study conducted by Sidibe, 2014, a biochar filter column achieved a bacterial reduction of approximately 1.5 log units for *Enterococcus faecalis*. Although this bacterium differs from *E. coli*, it was still considered sufficiently relevant as a bacterial indicator organism. However, due to absence of other similar sources, the same value was assigned for wood charcoal reduction in the QMRA.

Finally, the influence of drip irrigation as an irrigation method was evaluated as an alternative to manual bucket irrigation. This was considered relevant since the long-term plan at the school is to implement drip irrigation systems for agricultural activities. With drip irrigation, direct operator exposure is eliminated. Consequently, the *Garden irrigation (operator)* exposure pathway is no longer considered relevant. According to World Health Organization, 2006c, drip irrigation can contribute an additional pathogen reduction of approximately 2–4 log units for consumers of the crops, depending on crop type and irrigation configuration. Therefore, a 3-log reduction was selected for drip irrigation in the QMRA.

The different treatment and risk reduction options were compared using box plots of the resulting DALY distributions for Area I. The comparisons for the *Garden irrigation* scenario are presented in Figure 5.26, while the corresponding results for the *Raw vegetable consumption* scenario are presented in Figure 5.27.

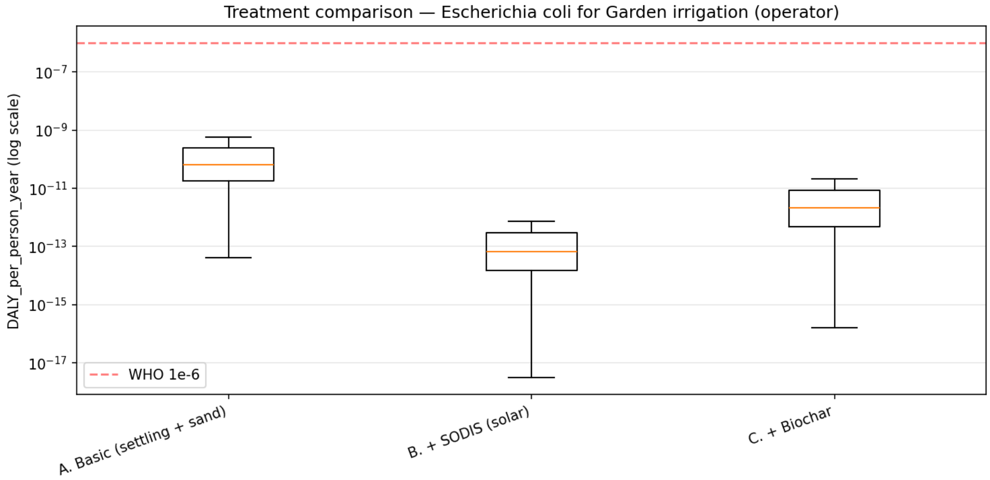


Figure 5.26: Comparison of additional treatment scenarios for *E. coli* in the *Garden irrigation (operator)* exposure pathway. The box plots show the DALY per person per year on a log scale, and the red dashed line represents the WHO reference value of 10^{-6} DALY pppy.

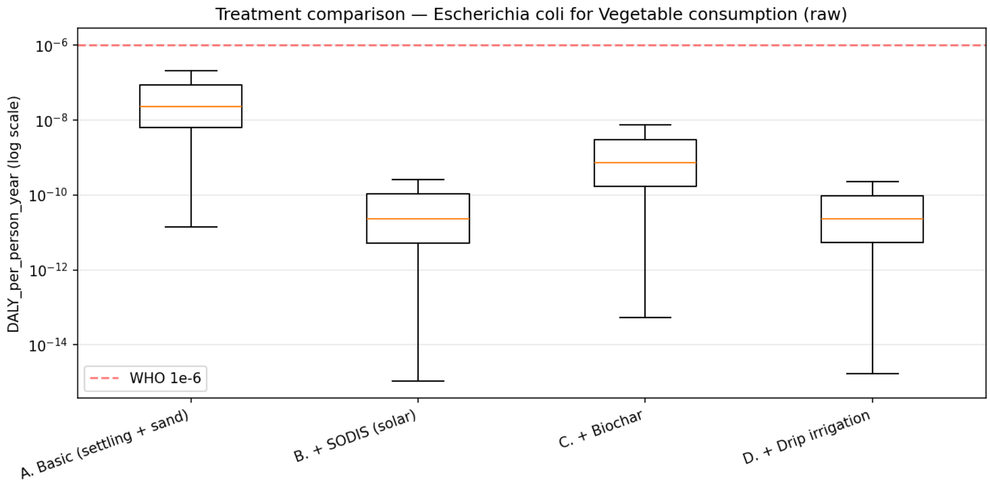


Figure 5.27: Comparison of additional treatment and risk reduction scenarios for *E. coli* in the *Raw vegetable consumption* exposure pathway. The box plots show the DALY per person per year on a log scale, and the red dashed line represents the WHO reference value of 10^{-6} DALY pppy.

The results presented in the Figures 5.26 and 5.27 indicate that SODIS and drip irrigation provided the largest additional reductions in estimated *E. coli* DALY values among the evaluated scenarios. Although the baseline treatment system consisting of a septic tank followed by sand filtration already fulfilled the WHO DALY target under normal operating conditions for both scenarios, it is still important to evaluate potential additional barriers in order to increase the robustness and long-term reliability of the system.

The additional barriers evaluated in this study should therefore be regarded only as preliminary examples of potential risk reduction measures. A more comprehensive evaluation would be required to determine which alternative is most suitable for implementation at Tumaini Open School. Such an assessment would need to consider not only pathogen reduction performance, but also factors such as cost, operation and maintenance requirements, technical complexity, material availability, scalability, and long-term sustainability. The presented box plots should therefore primarily be interpreted as an initial indication of how different additional barriers may influence the estimated health risks associated with greywater reuse.

5.8 Implications of the proposed greywater reuse system

In the future, if the proposed greywater treatment and reuse system is implemented at Tumaini Open School, its implementation will influence the people living and working at the school, the learning centre as an organisation, and the surrounding environment. In addition to the technical treatment performance evaluated in the previous sections, the proposed system may therefore also have other types of implications. Furthermore, the implementation of the system aligns with several of the United Nations Sustainable Development Goals (SDGs) developed by the United Nations (United Nations, n.d.).

5.8.1 Social and economic aspects

With the proposed treatment solution, it is important to consider how the system could influence the teachers and students living at Tumaini Open School, both positively and negatively. The implementation of the system would overall not drastically change their daily routines, since the municipal water would still be available for necessary activities. For the treatment system to function effectively, certain behavioural changes would be required. This includes disposing of greywater at designated locations to facilitate its collection. Furthermore, irrigation practices may need to be modified to ensure the safe reuse of treated greywater for irrigation. Therefore, it is important that the users of the system receive sufficient information regarding potential health risks and how the treated greywater should be handled safely.

Information and education regarding the system are therefore important not only from a social acceptance perspective, but also from a human health perspective, as discussed in Section 5.7. This can be connected to SDG 3: *Good Health and Well-being* (United Nations, n.d.), since the proposed system aims to reduce exposure to untreated wastewater, improve local water management, and minimise health risks associated with greywater reuse. The proposed treatment and reuse system can also be connected to SDG 6: *Clean Water and Sanitation* (United Nations, n.d.), particularly through the promotion of wastewater treatment, safe reuse of water, and improved water-use efficiency under water-scarce conditions. Furthermore, the system also aligns with SDG 9: *Industry, Innovation and Infrastructure* (United Nations, n.d.), by promoting the development of a locally adapted greywater treatment infrastructure suitable for decentralised wastewater management in low-resource settings.

Implementation of the proposed system would require financial investments for additional investigations, construction, and future operation and maintenance of the treatment system. Projects of this type are dependent on financial support from external organisations and partners to the school. However, if successfully implemented and maintained, the system could contribute to the long-term goal of increasing self-sufficiency at Tumaini Open School by reducing the dependence on municipal water supplies and improving water availability for food production. Improved water availability during dry periods could also make it possible for the school to increase agricultural production and potentially sell some of the produced crops. This could contribute to economic growth at the school and reduce the dependence on external financial support over time.

Moreover, nutrient recycling, as discussed in Section 2.3.1, represents a potential advantage of using greywater for irrigation, as it can reduce the need for synthetic fertilizers. This further supports the school's aim of becoming self-sufficient by utilizing resources generated on-site. However, since exact nutrient concentrations were not measured in this study, the potential benefits of nutrient recycling require further evaluation.

5.8.2 Ecological aspects

From an ecological perspective, the proposed greywater treatment and reuse system could improve the current water management practices at Tumaini Open School. At present, most of the generated greywater is discharged directly into the surrounding environment without treatment. Direct discharge of untreated greywater contribute to contamination of soil and groundwater (Oteng-Peprah et al., 2018). By treating and reusing the greywater instead, the environmental impacts from disposal at the school will be reduced. This can also be related to SDG 15: *Life on Land* (United Nations, n.d.), since improved wastewater management may help reduce pollution of surrounding soil and ecosystems.

Although treatment and reuse of greywater may provide environmental benefits, it is also important to acknowledge that the proposed system may still pose environmental risks if not properly managed. For example, irrigation with treated greywater can affect soil quality and the surrounding environment over time (Food and Agriculture Organization of the United Nations, 2003). Potential impacts include accumulation of salts, nutrients, and other pollutants in the soil, which in the long term may influence soil fertility, crop productivity, and local environmental conditions (Shui Lee, 2012). One of the main greywater sources with high salt content originates from laundry. Powdered detergents, as used in Area I, have been linked to decreased soil conductivity and humus removal to a greater extent compared to liquid detergents (Hardie et al., 2021). Therefore, from an ecological aspect, the powdered detergent could be substituted to a liquid detergent to decrease this risk. However, the risk remains a concern and should be investigated further, as proposed in the following section.

5.8.3 Future development and recommendations

Based on the findings and limitations identified in this project, several areas for further investigation are proposed. One important aspect is the collection and conveyance infrastructure for greywater, as this was not evaluated within the scope of the project. This includes the assessment of pipe dimensions, hydraulic flow conditions, and whether pumping would be required in certain locations or if the system could partially operate by gravity flow. Additionally, the laundry station in Area I is assumed to be a prerequisite for collecting greywater from laundry activities. Therefore, further investigations regarding the design and construction of the laundry station are required prior to the implementation of the treatment system.

Furthermore, the future implementation of drip irrigation at Tumaini Open School is another area that requires further investigation. Drip irrigation has the potential to increase the cultivated area through reduced irrigation demand and lower labour requirements compared to manual irrigation. It is therefore considered an important area for future research to further improve the school's self-sufficiency. In addition, as discussed in Section 5.7, drip irrigation could also contribute to reduced health risks associated with greywater reuse. Further investigations are needed to determine the required elevation of the storage tanks, as sufficient hydraulic pressure must be ensured for the drip irrigation system to function properly.

Another important area for future investigation is the measurement of *E. coli* in both influent and effluent greywater. To ensure that the proposed treatment system is sufficient and can provide water that is safe for irrigation reuse. This would allow the treatment performance to be verified under site-specific conditions and help confirm the assumptions and results of the QMRA.

Nutrient recycling should also be investigated further, as it can reduce the need for synthetic fertilizers and thereby lower operational costs. Therefore, concentrations of nitrogen and phosphorus should be measured and evaluated to determine the potential contribution of greywater reuse to nutrient recovery and agricultural production.

Finally, further assessment of salinity-related risks is recommended prior to large-scale implementation of the proposed greywater reuse system. As discussed in Section 5.4, the average EC of the treated greywater exceeded the threshold for no restriction on irrigation use and instead fell within the category of slight to moderate restriction (Food and Agriculture Organization of the United Nations, 2003). The elevated salinity may contribute to long-term salt accumulation in the soil, particularly in semi-arid regions such as Tabora (FAO, 1985). Therefore, future studies should consider determining the sodium adsorption ratio (SAR), which is a commonly used indicator for assessing potential infiltration problems associated with excess sodium in irrigation water. Such an assessment could provide additional insight into the long-term impacts of greywater irrigation on soil structure and help ensure the long-term sustainability of agricultural practices at Tumaini Open School.

6 Conclusion

The study addresses water scarcity at Tumaini Open School in rural Tanzania through greywater treatment and reuse. The reclaimed greywater will be used for irrigation in order to decrease the reliance on the municipal water supply. Thereby, the school will increase its resilience during the dry season and move towards the goal of becoming self-sufficient.

Greywater is generated at multiple locations across the school and is currently discharged directly onto the ground without treatment. Two separate treatment systems are proposed for Area I and Area III, respectively, with similar configurations but different dimensions. Each system consists of a septic tank for pre-treatment and temporary storage of greywater. The greywater is thereafter intermittently dosed onto a sand filter for further treatment.

Based on the assumptions applied in the QMRA, the estimated health risks associated with greywater reuse were within the acceptable range defined by WHO guidelines. However, these results should be regarded as indicative, as the assessment relied on literature-based pathogen concentrations and assumed treatment performances rather than site-specific microbiological measurements.

The proposed treatment solution has the potential to increase the cultivated area during the wet season while potentially eliminating the need for municipal water for irrigation. During the dry season, it can support a larger irrigation demand, either by reducing most of the school's dependence on municipal water or by enabling cultivation of larger areas and increase food production. However, the system is not sufficient to fully replace the municipal water throughout the year. Nevertheless, it represents one component of a more sustainable and resource-efficient water management system.

The evaluation of students' and staff members' attitudes towards greywater reuse indicated generally positive perceptions, particularly when treatment was included and sufficient information and training were provided. This suggests favourable conditions for successful long-term implementation of the proposed system.

Future studies should investigate the conveyance infrastructure from the greywater sources to the treatment systems, as well as conduct more detailed water quality and soil analyses. Additionally, drip irrigation should be evaluated to reduce both water consumption and human health risks.

7 AI disclosure

Artificial intelligence (AI) tools, such as Chat GPT, were used in this report to support language revision and improve grammar. Text originally written by the authors have in some cases been restructured using AI to improve clarity and readability in English. AI was also used to assist with programming-related questions and to identify and resolve technical issues encountered during the project.

All sections developed with the assistance of AI were subsequently reviewed and critically assessed by the authors. All final interpretations, calculations, and conclusions were made by the authors, who take full responsibility for the accuracy of the work.

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A Supplementary Field Data

This appendix presents supplementary data and supporting material used in the development and evaluation of the proposed greywater reuse system. The material includes field observations, water consumption records, information on detergent products used at the school, and MATLAB code developed for the greywater generation analysis. Together, these data provide additional context and support for the methods, assumptions, and design decisions presented in the main report.

A.1 MATLAB code for greywater generation profile

The MATLAB code below was used to develop the weekly greywater generation profile for Area I. Estimated monthly greywater volumes were converted into weekly volumes and combined with the temporal distributions obtained from the household surveys.

Listing A.1: MATLAB code for greywater generation profile in Area I

```
clc; clear; close all;
% Area I
% Greywater generation

Vmonth.shower      = 15954;
Vmonth.laundry     = 5602;
Vmonth.kitchen     = 2034;
Vmonth.handwashing = 290;
Vmonth.handbasin   = 1917;

days_month = 30;
days_week  = 7;

%% Convert monthly volume to weekly volume

Vweek.shower      = Vmonth.shower      / days_month * days_week;
Vweek.laundry     = Vmonth.laundry     / days_month * days_week;
Vweek.kitchen     = Vmonth.kitchen     / days_month * days_week;
Vweek.handwashing = Vmonth.handwashing / days_month * days_week;
Vweek.handbasin   = Vmonth.handbasin   / days_month * days_week;

%% Weekly distributions

% Laundry profile
week.laundry = [0.0175 0.0351 0.386 0.035 0.018 0.386 0.123];

% Other sources distributed evenly over the week
week.shower      = [0.142857143 0.142857143 0.142857143 0.142857143
    0.142857143 0.142857143 0.142857143];
week.kitchen     = [0.142857143 0.142857143 0.142857143 0.142857143
    0.142857143 0.142857143 0.142857143];
week.handwashing = [0.142857143 0.142857143 0.142857143 0.142857143
    0.142857143 0.142857143 0.142857143];
week.handbasin   = [0.142857143 0.142857143 0.142857143 0.142857143
    0.142857143 0.142857143 0.142857143];

%% Daily distributions
%[Before breakfast, Between breakfast and lunch, Between lunch and
    dinner, After dinner]
```

```
day.laundry     = [0.633 0.1 0.1 0.167];
day.shower      = [0.489 0.043 0.149 0.319];
day.kitchen     = [0 0.333333333 0.333333333 0.333333333];
day.handbasin   = [0 0.333333333 0.333333333 0.333333333];
day.handwashing = [0.25 0.25 0.3125 0.1875];

%% Normalize distributions to avoid tiny errors from excel calculaitons
week.laundry     = week.laundry     / sum(week.laundry);
week.shower      = week.shower      / sum(week.shower);
week.kitchen     = week.kitchen     / sum(week.kitchen);
week.handwashing = week.handwashing / sum(week.handwashing);
week.handbasin   = week.handbasin   / sum(week.handbasin);

day.laundry      = day.laundry      / sum(day.laundry);
day.shower       = day.shower       / sum(day.shower);
day.kitchen      = day.kitchen      / sum(day.kitchen);
day.handbasin    = day.handbasin    / sum(day.handbasin);
day.handwashing  = day.handwashing  / sum(day.handwashing);

%% Hours in each interval

% 00-06   = 6 h, zero flow
% 06-10   = 4 h, before breakfast
% 10-14   = 4 h, between breakfast and lunch
% 14-19   = 5 h, between lunch and dinner
% 19-23   = 4 h, after dinner
% 23-24   = 1 h, zero flow

hours = [4 4 5 4];

%% Build weekly profiles

shower      = build_week(Vweek.shower,      week.shower,      day.shower,      hours);
laundry     = build_week(Vweek.laundry,     week.laundry,     day.laundry,     hours);
kitchen     = build_week(Vweek.kitchen,     week.kitchen,     day.kitchen,     hours);
handwashing = build_week(Vweek.handwashing, week.handwashing, day.handwashing, hours);
handbasin   = build_week(Vweek.handbasin,   week.handbasin,   day.handbasin,   hours);

total = shower + laundry + kitchen + handwashing + handbasin;

t = 1:168;
day_names = {'Mon','Tue','Wed','Thu','Fri','Sat','Sun'};

%% Stacked area plot

figure('Color','w');
A = [shower laundry kitchen handwashing handbasin];
area(t, A, 'LineStyle', 'none')
grid on
box on
title('Stacked␣weekly␣greywater␣profile␣-␣Area␣I')
```

```
xlabel('Day␣of␣week')
ylabel('Volume␣(L/h)')
xticks([1 25 49 73 97 121 145])
xticklabels(day_names)
xlim([1 168])

legend('Shower','Laundry','Kitchen','Handwashing','Dormitory␣basin', ...
    'Location','northoutside','Orientation','horizontal')

hold on
for x = [24.5 48.5 72.5 96.5 120.5 144.5]
    xl = xline(x,'--k','LineWidth',0.8);
    xl.Annotation.LegendInformation.IconDisplayStyle = 'off';
end
hold off

%% Peak analysis

[max_peak, idx_peak] = max(total);

day_num = ceil(idx_peak/24);
hour_in_day = mod(idx_peak-1,24);

fprintf('Total␣weekly␣greywater␣volume:␣%.2f␣L/week\n', sum(total));
fprintf('Maximum␣peak␣flow:␣%.2f␣L/h\n', max_peak);
fprintf('Peak␣occurs␣on␣%s␣at␣%02d:00-%02d:00\n', ...
    day_names{day_num}, hour_in_day, mod(hour_in_day+1,24));

%% Top 10 peak hours

[sorted_vals, sorted_idx] = sort(total, 'descend');

fprintf('\nTop␣10␣hourly␣peaks:\n');
fprintf('Rank\tHour\tDay\tTime\t\tFlow␣(L/h)\n');
for i = 1:10
    d = ceil(sorted_idx(i)/24);
    h = mod(sorted_idx(i)-1,24);
    fprintf('%d\t%d\t%s\t%02d:00-%02d:00\t%.2f\n', ...
        i, sorted_idx(i), day_names{d}, h, mod(h+1,24), sorted_vals(i));
end

%% Daily totals

fprintf('\nDaily␣totals:\n');
for d = 1:7
    ind = (d-1)*24 + (1:24);
    fprintf('%s:␣%.2f␣L/day\n', day_names{d}, sum(total(ind)));
end

%% Source weekly total
fprintf('\nSource␣totals:\n');
fprintf('Shower:␣%.2f␣L/week\n', sum(shower));
fprintf('Laundry:␣%.2f␣L/week\n', sum(laundry));
fprintf('Kitchen:␣%.2f␣L/week\n', sum(kitchen));
fprintf('Handwashing:␣%.2f␣L/week\n', sum(handwashing));
fprintf('Dormitory␣basin:␣%.2f␣L/week\n', sum(handbasin));
```

```
%% Weekly profile

function profile = build_week(Vweek, week_dist, day_dist, hours)

profile = zeros(168,1);

for d = 1:7

    Vday = Vweek * week_dist(d);

    V1 = Vday * day_dist(1); % Before breakfast
    V2 = Vday * day_dist(2); % Between breakfast and lunch
    V3 = Vday * day_dist(3); % Between lunch and dinner
    V4 = Vday * day_dist(4); % After dinner

    day_profile = [
        zeros(6,1)              % 00-06
        repmat(V1/hours(1),4,1) % 06-10
        repmat(V2/hours(2),4,1) % 10-14
        repmat(V3/hours(3),5,1) % 14-19
        repmat(V4/hours(4),4,1) % 19-23
        0                       % 23-24
    ];

    profile((d-1)*24+1:d*24) = day_profile;
end

end
```

A.2 MATLAB code for dimensioning of sand filter and septic tank

The MATLAB code below was used to develop the dimenisons for the final treatment solution in Area I, The same code but with different inputs was used for Area III.

Listing A.2: MATLAB code for dimensioning of final treatment solution

```
%% Sizing of tank and intermittent sand filter AREA I
clear; clc;

%% Inputs
Q_daily = [696 719 1177 719 697 1177 833];   % [L/day]

safety_factor = 1.35; %Based on sensistivty analysis of varying
    greywater generation factors

% Adjust daily flows with safety factor
Q_daily_design = Q_daily * safety_factor;     % [L/day]

% Constant daily outflow to sand filter
Qout_daily = mean(Q_daily_design);            % [L/day]
Qout_daily_m3 = Qout_daily/1000;              % [m3/day]

%% PARAMETER RANGES
HLR_range = 80:10:200;              % [L/m2/day]
dose_range = 4:1:12;                 % [doses/day]
```

```
dose_depth_range = 0.05:0.01:0.076;  % [m/dose]

%%  Tank water balance
storage = 0;
storage_profile = zeros(1, length(Q_daily_design));

for d = 1:length(Q_daily_design)

    Qin = Q_daily_design(d);   % [L/day]
    Qout = Qout_daily;         % [L/day]

    storage = storage + Qin - Qout;

    % Tank cannot have negative storage
    if storage < 0
        storage = 0;
    end

    storage_profile(d) = storage;
end

% Volume needed from water balance
V_balance = max(storage_profile)/1000;    % [m3]

%% Required tank volume
% Tank volume is determined by a worst case combination:
% 1) 24 h storage and settling of largest daily inflow
% 2) largest storage volume during a week
Vtank_required = max(storage_profile)/1000 + max(Q_daily_design/1000);

%% Results
results = [];

%% Loop through filter options
for HLR = HLR_range
    for n_doses = dose_range
        for dose_depth = dose_depth_range

            % Dose volume
            Q_dose = Qout_daily / n_doses;      % [L/dose]

            % Filter area from HLR
            A_HLR = Qout_daily / HLR;           % [m2]

            % Filter area from dose depth
            A_dose = (Q_dose/1000) / dose_depth; % [m2]

            % Required filter area
            A_filter = max(A_HLR, A_dose);      % [m2]

            % Actual filter parameters
            HLR_actual = Qout_daily / A_filter;           % [L/m2/day]
            dose_depth_actual = (Q_dose/1000) / A_filter; % [m]

            % Most important parameters
            w_area = 1.0;
```

```
            w_HLR = 2.0; % tried both 2 and 1.5, more important due to clogging

            score = w_area*A_filter + w_HLR*(HLR_actual/100);

            % Results based on different values
            results = [results;
                HLR, n_doses, dose_depth, Q_dose, Qout_daily, ...
                A_filter, HLR_actual, dose_depth_actual, ...
                V_balance, Vtank_required, score];
        end
    end
end

%% Table with results
T = array2table(results, ...
    'VariableNames', {'HLR_input_L_m2_d', ...
    'Doses_per_day', ...
    'Dose_depth_input_m', ...
    'Dose_volume_L', ...
    'Qout_daily_L_day', ...
    'Filter_area_m2', ...
    'HLR_actual_L_m2_d', ...
    'Dose_depth_actual_m', ...
    'V_balance_m3', ...
    'Tank_volume_m3', ...
    'Score'});

% sort results
T_valid = sortrows(T, 'Score', 'ascend');

disp('Best␣design␣alternatives:')
disp(T_valid(1:min(20,height(T_valid)), :))

%% Best option based on the score
best = T_valid(1,:);

fprintf('\nBest␣option:\n')
fprintf('HLR␣=␣%.0f␣L/m2/day\n', best.HLR_actual_L_m2_d)
fprintf('Doses␣per␣day␣=␣%.0f\n', best.Doses_per_day)
fprintf('Dose␣volume␣=␣%.1f␣L/dose\n', best.Dose_volume_L)
fprintf('Daily␣outflow␣to␣filter␣=␣%.1f␣L/day\n', best.Qout_daily_L_day)
fprintf('Dose␣depth␣=␣%.3f␣m/dose\n', best.Dose_depth_actual_m)
fprintf('Filter␣area␣=␣%.2f␣m2\n', best.Filter_area_m2)
fprintf('Required␣tank␣volume␣=␣%.2f␣m3\n', best.Tank_volume_m3)
```

A.3 Monthly invoices from Tumaini Open School

The monthly invoices were provided from the headmaster at Tumaini Open School and displayed in Table A.1.

Table A.1: Monthly water consumption for each area at Tumaini Open School.

Month	Area I	Area II	Area III	Total
January	20000	13000	25000	58000
February	69000	16000	9000	94000
March	66000	31000	19000	116000
April	68000	38000	14000	120000
May	70000	47000	13000	130000
June	101000	51000	12000	164000
July	55000	27000	15000	97000
August	64000	47000	14000	125000
September	76000	23000	21000	120000
October	56000	78000	25000	159000
November	80000	61000	26000	167000
December	46000	28000	43000	117000
Total	771000	460000	236000	1467000
January 2026	45000	18000	25000	88000
February 2026	41000	18000	23000	82000

A.4 Observation checklist results

The compiled results from the observation checklist is displayed in table A.2.

Table A.2: Observed toilet usage distribution during the day.

Period	Left toilet	Right toilet	Comment
Before breakfast	10	20	
Between breakfast and lunch	46	117	Pen gone, some brought their own.
Between lunch and dinner	81	62	Pen gone again.
After dinner	0	0	No pen and dark.
Night	0	0	Assumed no activity.

A.5 Detergent chemicals

The detergent chemicals are displayed in Table A.3, based on the containers seen during the field studies.

Table A.3: Ingredients in the detergents used at Tumaini Open School

Product	**Ingredients**
Doffi washing powder	Surfactants, sodium tripolyphosphate, sodium sulfate, sodium carbonate, sodium silicate, optical brighteners (OBS), proteolytic enzymes, perfumes
Dexi fabric wash	Anionic, non-ionic and amphoteric surfactants, optical brighteners, perborate, preservatives, de-mineralized water, colour, scents
Dexi dish wash	Anionic and amphoteric surfactants, citric acid, sodium chloride, perfume, de-mineralized water

B Questionnaire material

This appendix contains the questionnaires used in the study to investigate water use behaviour, greywater generation patterns, and perceptions regarding greywater reuse among students and staff at Tumaini Open School.

B.1 Water use behaviour questionnaire

Hello!
We (Johanna & Yasmine) would like to ask you some questions about water use at the school. Your answers will help us better understand how water is used and how it can be improved in the future. It would be very helpful for us if you could take a few minutes to answer the questions below. Thank you for your help!

Question 1: How often do you usually do laundry? ☐ Three times per week
☐ Two times per week
☐ One time per week
☐ Once every two weeks

Question 2: Which days do you usually do laundry? *You should choose more than one option if your laundry days vary.*
☐ Monday
☐ Tuesday
☐ Wednesday
☐ Thursday
☐ Friday
☐ Saturday
☐ Sunday

Question 3: When during the day do you usually do laundry? ☐ Before breakfast
☐ Between breakfast and lunch
☐ Between lunch and dinner
☐ After dinner

Question 4: How many buckets of water do you usually use when you do your laundry? ☐ 1
☐ 2
☐ 3
☐ 4
☐ 5 or more

Question 5: How many times a day do you wash your hands at the toilet by the school? ☐ 1
☐ 2
☐ 3
☐ 4 or more

Question 6: How many times a day do you wash your hands at the toilet by the dormitory? ☐ 1
☐ 2
☐ 3

☐ 4 or more

Question 7: This sink between the dormitory and dining hall, what is the main activity here? ☐ Handwashing
☐ Doing dishes

Question 8: How many times a day do you wash your hands/do your dishes at the sink between the dormitory and dining hall? ☐ 0
☐ 1
☐ 2
☐ 3
☐ 4 or more

Question 9: This sink outside the school kitchen, what is the main activity here? ☐ Handwashing
☐ Doing dishes

Question 10: How many times a day do you wash your hands/do your dishes at the sink outside the school kitchen? ☐ 0
☐ 1
☐ 2
☐ 3
☐ 4 or more

Question 11: How often do you use the shower room? ☐ Twice a day
☐ Once a day
☐ Once every two days
☐ Twice a week
☐ Once a week

Question 12: How many buckets do you usually use when showering? ☐ 1
☐ 2
☐ 3
☐ 4
☐ 5 or more

Question 13: When during the day do you usually shower? *You can choose two options if you shower twice a day.*
☐ Before breakfast
☐ Between breakfast and lunch
☐ Between lunch and dinner
☐ After dinner

B.2 Greywater reuse questionnaire

Information to participants

Responses are anonymous and will only be used for research purposes. Participation is voluntary and you may skip any question if you prefer. There are no right or wrong answers. We are only interested in your opinion.

1. How old are you? ______________
2. Role at the school?

☐ Student ☐ Teacher ☐ Staff ☐ Other

3. Level of education
☐ Primary ☐ Secondary ☐ Bachelor ☐ Masters

4. How long have you been at the school?
☐ <1 month ☐ 1–6 months ☐ 6–12 months ☐ 1–2 years
☐ 2–3 years ☐ >3 years

5. What water sources are currently used for irrigation?
☐ Municipal drinking water ☐ Water from the well ☐ Rainwater
☐ Reused water (laundry/kitchen) ☐ Other: _________

6. How often does the municipal water supply stop working?
☐ Every week ☐ Twice per month ☐ Once per month ☐ Rarely

7. Does water availability vary between seasons? If yes, when is it most limited?
☐ Dry season ☐ Wet season ☐ No difference

8. Who is mainly responsible for irrigation?
☐ Students ☐ Staff

9. How important is water availability for school activities (e.g. gardening)?
☐ Very important ☐ Somewhat important
☐ Not very important ☐ Not important

10. Before this survey, were you familiar with the term greywater?
☐ Yes ☐ No

11. Do you think greywater can be reused for non-potable purposes?
☐ Yes ☐ No

12. What do you think is the main benefit of reusing greywater?
☐ Reduced water use ☐ Irrigation during dry periods
☐ Saves money ☐ Environmental benefits
☐ No benefits ☐ Other: _________

13. I would feel comfortable reusing untreated greywater for irrigation
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

14. I would feel comfortable reusing treated greywater for irrigation
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

15. I am concerned about health risks related to greywater reuse
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

16. I am concerned about environmental effects of greywater reuse
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

17. Reusing greywater could help reduce water scarcity
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

18. I would be willing to reuse greywater for irrigation
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

19. I would trust a system that treats greywater
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

20. Would you accept greywater reuse for:

Use	Yes	Maybe	No
Irrigation of trees	☐	☐	☐
Irrigation of flowers	☐	☐	☐
Irrigation of crops	☐	☐	☐
Flushing toilets	☐	☐	☐
Construction activities	☐	☐	☐

21. What concerns you about greywater reuse? (multiple answers possible)
    ☐ Health risks ☐ Smell ☐ Water quality
    ☐ Environmental effects ☐ No concerns
    ☐ Other: __________

22. What would make you more comfortable reusing greywater?
    ☐ Treatment of the water ☐ Clear information about safety
    ☐ Training ☐ Other: __________

23. Would you be willing to help maintain a greywater system?
    ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

24. Who should be responsible for managing a greywater system?
    ☐ School staff ☐ Students ☐ Shared responsibility

25. Are there any cultural or religious concerns related to greywater reuse?
    ☐ Yes ☐ No ☐ Not sure
    If yes, please explain: ____________________

C Supplementary experimental results

This appendix presents additional experimental results and figures supporting the evaluation of the greywater treatment prototype.

C.1 Turbidity removal graph

Figure C.1 provides supplementary results showing how turbidity removal varied with the cumulative number of charcoal bed volumes treated during prototype operation.

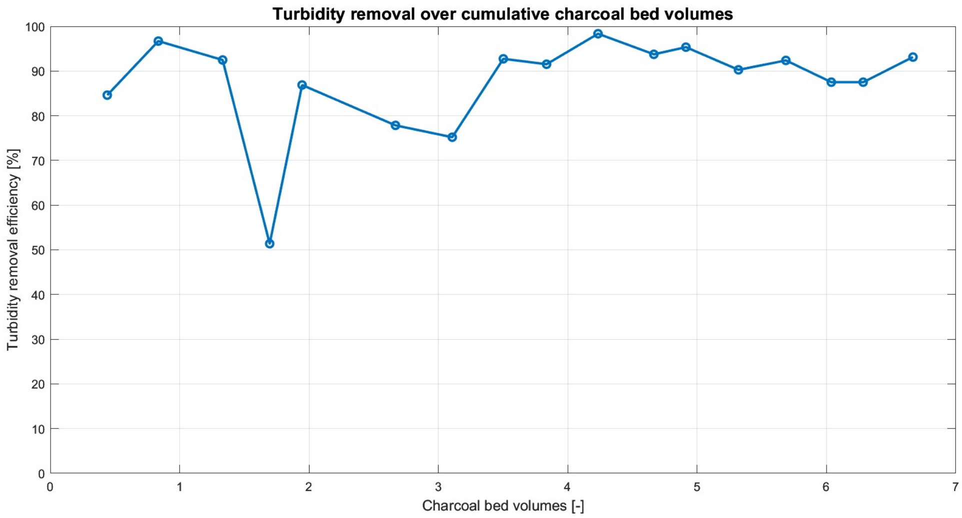

Figure C.1: Turbidity removal [%] over cumulative charcoal bed volumes.

D Proposed treatment solution for Area III

This appendix presents the proposed treatment solution for Area III. The overall design approach, assumptions, and calculation methods are the same as those presented for Area I in Section 5.6. However, since Area III differs in terms of greywater sources, flow conditions, and site-specific prerequisites, the calculations and design modifications specific to Area III are presented separately in this appendix.

D.1 Septic tank

The vertical section of the septic tank is visualized in Figure D.1. The design parameters are shown in Table D.1.

Table D.1: Design parameters for the septic tank in Area III

Parameter	Value	Unit
Length	2	m
Width	1.12	m
Height	1.12	m
T-baffle above surface	9	cm
T-baffle under surface	19	cm

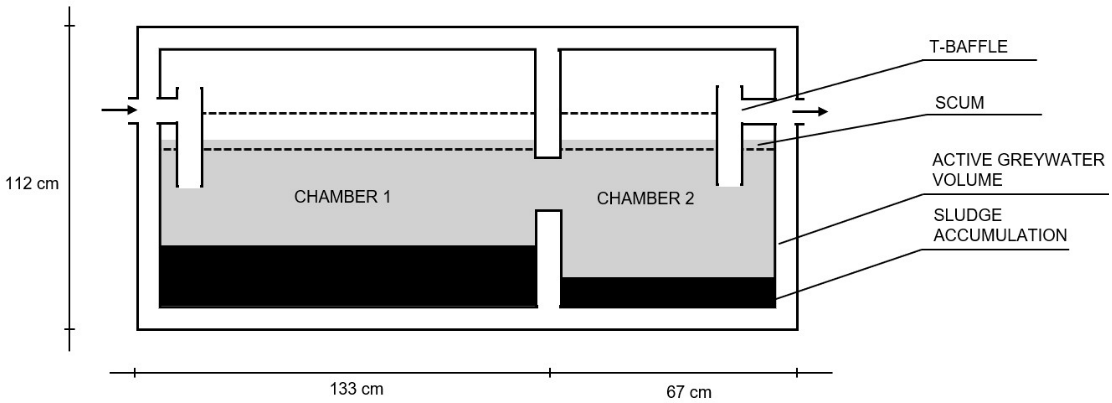

Figure D.1: Vertical section of septic tank in Area III

D.2 Intermittent sand filter

The design parameters for the intermittent sand filter in Area III are presented in Table D.2, while the vertical section and distribution pipe layout are shown in Figure D.2 and Figure D.3.

Table D.2: Design parameters of the ISF in Area III

Parameter	Value	unit
HLR	180	L/m^2/d
Doses	4	st/d
Q_{design}	648	L/d
Q_{dose}	162	L/dose
Filter Area	3.6	m^2
Lateral pipe spacing	33	cm
Orifice spacing	30	cm
Orifice size	4	mm

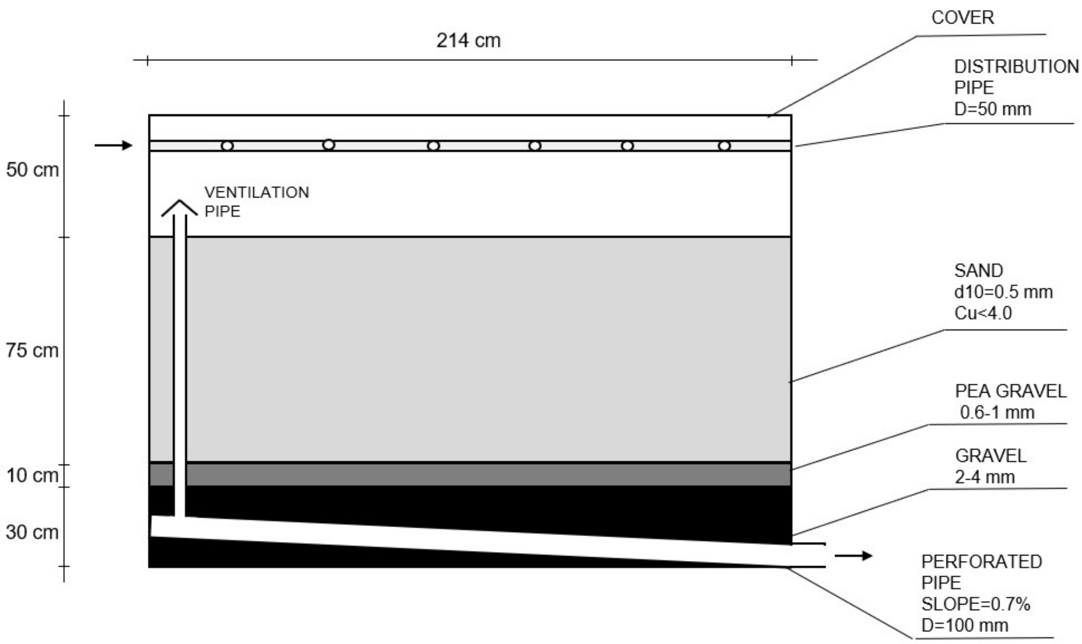

Figure D.2: Vertical section of intermittent sand filter in Area III, including diameter, bed depths and grain sizes

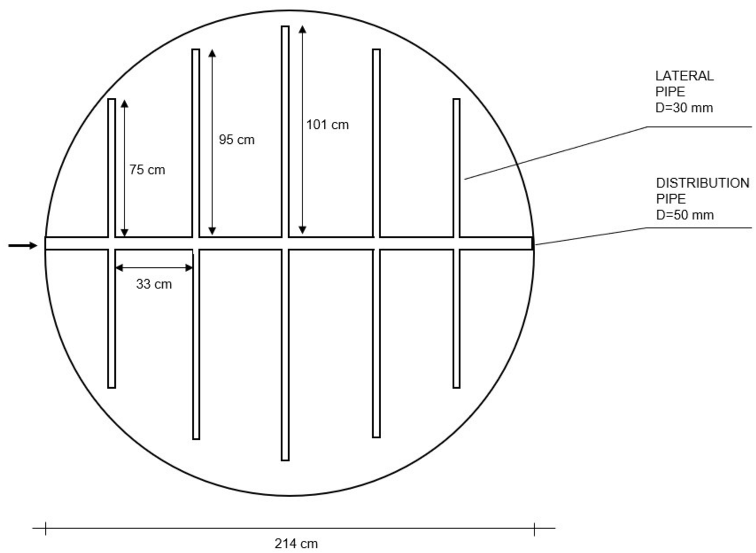

Figure D.3: Above section of filter and distribution pipes in Area III

D.3 Storage tank

The required storage tank volume for Area III was calculated to approximately 1350 L (1.35 m^3). This was based on a weekly greywater generation of 3157.78 L/week and the design criterion of storing up to three consecutive days of treated greywater, as described in Section 5.6.6. For Area I, it was suggested that the final tank size should be selected based on locally available standard dimensions, with the existing 5 m^3 tanks at the school used as an example. However, since the required storage volume in Area III is substantially smaller, a 5 m^3 tank is considered unnecessarily large. Therefore, a smaller plastic tank with a volume closer to the required storage capacity is proposed for Area III.

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