Technical University of Denmark
Department of Environmental and Resource Engineering

Master's Thesis

Treatment of Greywater in the Arctic:

A Water, Sanitation and Hygiene (WASH) study

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Preface

This Master's Thesis, entitled "Treatment of Greywater in the Arctic: A Water, Sanitation and Hygiene (WASH) study", is submitted by Agata Magdalena Pruss (student number 222917) for the degree of Master of Science in Environmental Engineering in the study line of Water Technology and Management.

Presented work was carried out in the period from the 26th of August 2024 to the 25th of January 2025 with the extension due to unforeseen circumstances until the 30th of January 2025 (equivalent to 30 ECTS) at the Section of Materials and Durability, Department of Environmental and Resource Engineering (DTU Sustain), Technical University of Denmark (DTU), in partnership with DTU National Food Institute and Qeqqata Municipality in Greenland.

The project was conducted under the supervision of Associate Professor Pernille Erland Jensen, Professor Lisbeth Truelstrup Hansen (DTU Food), and external supervisor Professor Eberhard Morgenroth from the Swiss Federal Institute of Aquatic Science and Technology (Eawag). Technical guidance was received from the Laboratory Coordinator Ebba Cederberg Schnell.

AI-based applications (Google Translate, ChatGPT – version 4o and Grammarly) were used in the research work for translation between English, Danish and Greenlandic (*Kalaallisut*) as well as for spelling and grammar checks. The author is aware of her responsibility for the entire thesis content.

It is assumed that the reader has a basic knowledge of the field of environmental engineering.

Agata Pruss

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Agata Magdalena Pruss

30th of January 2025

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date

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Abstract

This study investigates water storage practices and greywater reuse in unpiped homes in Greenlandic settlements, highlighting the need for improved access to WASH hardware to prevent microbial contamination of water. The research was conducted in two phases: fieldwork in Greenland, and laboratory experiments at DTU in Denmark with a literature study. Fieldwork involved collecting data on household water storage and performing water quality analyses, while laboratory experiments focused on the feasibility of using Biologically Activated Gravity-Driven Membrane (GDM) technology and investigation on Point-of-Use disinfection for greywater recycling. The study found that greywater storage units exhibited high levels of microbial contamination, necessitating treatment before reuse. GDM technology showed potential for treating greywater but requires further research on nutrient-balancing and biofouling. Evaluated disinfection methods included boiling, NaDCC chlorine tablets, and UV-C LEDs, with boiling identified as the most favourable option due to its high water safety, cultural acceptance, and low initial cost. The study emphasizes the importance of addressing water storage practices and exploring robust, locally produced, and scalable greywater recycling technologies to improve water quality and public health in Greenlandic settlements.

Keywords: Greenlandic Settlements, WASH, Household Water Storage, Greywater Recycling, Point-of-Use Disinfection, Sustainability

Sammenfatning

Denne undersøgelse omhandler gråtvandsopbevaringspraksis og genbrug i hjem uden rørføring i grønlandske bosættelser og fremhæver behovet for forbedret adgang til WASH-udstyr for at forhindre mikrobiel forurening af vand. Undersøgelsen blev udført i to faser: Feltarbejde i Grønland samt laboratorieforsøg og litteraturundersøgelse på DTU i Danmark. Feltarbejdet involverede indsamling af data om husstandes vandopbevaring og udførelse af vandkvalitetsanalyser, mens laboratorieforsøg fokuserede på mulighederne for at genbruge gråtvand ved hjælp af Biologisk Aktiveret Gravity-Driven Membran (GDM)-teknologi samt undersøgelse af Point-of-Use-desinfektion til genbrug af gråtvand. Undersøgelsen fandt, at gråtvandsopbevaringsenheder udviste høje koncentrationer af mikrobiel forurening, hvilket nødvendiggør behandling før genbrug. GDM-teknologi viste potentiale til behandling af gråtvand, men kræver yderligere forskning i næringsstofbalancering og biofilmdannelse. Evalueringen af desinfektionsmetoder omfattede kogning, NaDCC-klortabletter og UV-C LED'er, hvor kogning blev identificeret som den mest fordelagtige mulighed på grund af dens høje vandsikkerhed, kulturelle accept og lave startomkostning. Undersøgelsen understreger vigtigheden af at adressere vandopbevaringspraksis og udforske robuste, lokalt producerede og skalerbare teknologier til genbrug af gråtvand for at forbedre vandkvaliteten og folkesundheden i grønlandske bosættelser.

Nøgleord: Grønlandske Bosættelser, WASH, Husstandsvandopbevaring, Genbrug af Gråtvand, Desinfektion ved Brugspunkt, Bæredygtighed

Naalisaaneq

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Oqaatsit pingaarnerit: Kalaallit Najugaqarfii, WASH, Illumi imermik toqqorsivik, Gråvand-imik atuineq, Atorfimmi Desinfektion, Piujuartitsineq

Table of Content

Preface iii
Acknowledgements iv
Abstract v
Sammenfatning v
Naalisaaneq vi
Table of Content vii
List of Figures x
List of Tables xiii
Abbreviations xiv
1 Introduction 15
1.1 Background 15
1.1.1 Arctic Region 15
1.1.1.1 Cold Climate Challenges 16
1.1.1.2 Greenland 16
1.1.2 Water, Sanitation and Hygiene (WASH) 19
1.1.2.1 WASH Barriers to Disease Prevention 19
1.1.2.2 Human Rights and Sustainable Development Goals 20
1.1.2.3 Guidelines and Standards on Access to WASH-services 20
1.1.2.4 WASH Sector in Greenland 20
1.1.3 Decentralized Greywater Recycling 31
1.1.3.1 Biologically Activated Gravity-Driven Membrane Technology 32
1.1.3.2 Point-of-Use Disinfection 33
1.1.4 Perspective on Sustainability 33
1.2 Project Objectives and Research Questions 34
2 Materials and Methods 35
2.1 Project Phases 35
2.2 Water Quality Analyses 35
2.2.1 Microbiological Parameters 35
2.2.1.1 Materials and Equipment 35
2.2.1.2 Quality Control Measures 35
2.2.1.3 Sample Handling and Preparation 36
2.2.1.4 Incubation and Reading 36
2.2.1.5 Data Analysis 36
2.3 Physico-Chemical Parameters 37
2.4 Fieldwork in Greenland 37
2.4.1 Outdoor Surveys 37

2.4.2 Observations and Photographs ... 37
2.4.3 Questionnaires and Interviews ... 37
2.4.4 Water Sampling and Testing ... 38
2.4.5 Model for Nutrient-Balancing Requirements ... 38
2.5 Laboratory Experiments in Denmark ... 39
2.5.1 Experimental Setup and Approach ... 39
2.5.1.1 Membrane Preparation ... 41
2.5.1.2 Feed Water ... 41
2.5.2 Operation of Experiment ... 42
2.5.2.1 Hydraulic Parameters ... 42
2.5.2.2 Removal Efficiency ... 43
2.5.3 SWOT Analysis for Future Study Recommendations ... 43
2.6 Selection of Disinfection Method ... 44
2.6.1 Functional Unit ... 44
2.6.2 Selection of Scenarios ... 44
2.6.3 Assessment Criteria Weights ... 44
2.6.4 Scenario Scoring ... 44
2.6.5 Decision Matrix ... 44
3 Results and Discussion ... 45
3.1 Household Water Storage ... 45
3.1.1 Water Sources ... 45
3.1.2 Water Gathering ... 45
3.1.3 Water Storage and Use ... 46
3.1.4 Key Findings on Household Water Storage ... 51
3.1.5 Nutrient-Balancing Requirements ... 52
3.2 Greywater Recycling ... 54
3.2.1 Biologically Activated Gravity-Driven Membrane ... 54
3.2.1.1 Permeate Flux and Biofilm Formation ... 54
3.2.1.2 Water Quality Parameters ... 57
3.2.1.3 Key Findings on GDM ... 62
3.2.1.4 SWOT Analysis and Future Study Recommendations ... 62
3.2.2 Point-of-Use Disinfection ... 64
3.2.2.1 Assessment Criteria ... 64
3.2.2.2 Criteria Weights ... 64
3.2.2.3 Scenario Scoring ... 65
3.2.2.4 Decision Matrix ... 68
3.2.3 Key Findings on Greywater Recycling ... 69
4 Conclusions ... 70
References ... 71

Appendices 77
A. Fieldwork Data 77
B. Laboratory Experiments Data 80
C. Katadyn Micropur Forte Tablets 84
D. Pearl Aqua Micro™ 86
E. Calculations for Disinfection Scenarios 88

List of Figures

Figure 1. The boundary of the Arctic Monitoring and Assessment Programme area with the Arctic marine boundary, Arctic circle and 10°C July isotherm ([1], edited by author). 15
Figure 2. Map of Greenland with the location of Sisimiut and Itilleq (made in QGIS using OpenStreetMaps [10]).......... 17
Figure 3. Distribution of the population in urban and rural areas of the Greenlandic municipalities (data for 2024 from StatBank Greenland [11]). 17
Figure 4. Sisimiut (a) on a map (made in QGIS version 3.22 based on data from OpenStreetMap [10]) and (b) in real life, August 2024. 18
Figure 5. Itilleq (a) on a map (made in QGIS version 3.22 based on data from OpenStreetMap [10]) and (b) in real life, September 2024. 19
Figure 6. UN Sustainable Development Goals logo with the icon of SDG6 (materials edited by the author [27]). 20
Figure 7. (a) Logo and regions of Nukissorfiit [31] with (b) the volumes of supplied water for households (red) and industries (grey) in Mm^3 over the years 2004-2023 (data from StatBank [35]). 22
Figure 8. Water production cost in DKK/m^3 for settlements and towns (Nukissiorfiit data [33]) divided by their water sources (data from Jupiter database [37]). 22
Figure 9. Intakes of (a) lake water in Sisimiut, August 2024, (b) groundwater and (c) seawater in Itilleq, September 2024. 23
Figure 10. (a) Sand filters and (b) NaOCl dosing station at the Sisimiut WTP, August 2024. (c) View to the inside on the Itilleq WTP, September 2024. 24
Figure 11. (a) Heated pipes above the ground supplying taphouse in Itilleq, September 2024. (b) Filling of the water truck at the water treatment plant in Sisimiut, August 2024. 24
Figure 12. Water supply in Itilleq (made in QGIS version 3.22 based on data from Asiaq Map Supply Service [49] and OpenStreetMap [10]). 25
Figure 13. Overview of water supply sources, treatment technologies, and conveyance methods in Greenland (made in Miro based on data from Nukissiorfiit [41], [47]). 26
Figure 14. An overview of sanitation systems for human waste collection in Greenlandic households (made in Miro inspired by Compendium of Sanitation Systems and Technologies [58]). 28
Figure 15. Sanitation in Itilleq: (a) dry toilet in the service house, (b) bags stored outside the household, (c) tractor with a shovel to pick up the bags, (d) latrine disposal site with a sea view, and (e) latrine disposal ramp, September 2024. 28
Figure 16. (a) "Chocolate factory" in Sisimiut discharging (b) wastewater into the sea, June 2023. 28
Figure 17. Greywater sources in unpiped homes: (a) bathroom sink and (b) kitchen sink with washbasin in Itilleq, September 2024. (c) Household greywater outlet in Sisimiut [60]. 29
Figure 18. Service house in Itilleq. Greywater from (a) showers, (b) washing and (c) laundry facilities is (d) discharged to the sea via the pipe, September 2024. 29
Figure 19. Average Heterotrophic Plate Count incubated at 37°C, total coliforms and E. coli in greywater samples collected from runoffs A-I in Sisimiut (data from [62]). The detection limit was 1 CFU/mL (0 log CFU/1 mL), shown as a dotted horizontal line. Non-detects are shown as ½ the detection limit (-0.301 log CFU/mL). Means within each microbial parameter are indicated by the short full horizontal line. 30
Figure 20. Cause-effect chain of WASH in the Greenlandic unpiped home (made in Miro). 31

Figure 21. (a) Field laboratory in Itilleq. (b) Microbial analyses in Itilleq. (c) Laboratory work in Sisimiut. (d) Laboratory work in Denmark. 35
Figure 22. AQHC Petrifilms™: (a) negative test control with filter, (b) plate with filter eligible for counting, (c) directly plated eligible for square-based colony count estimation and (d) directly plated assumed overgrown (300 CFU/1 mL). EC Petrifilms™: (e) negative test control with filter, (f) directly plated eligible for counting, (g) directly plated eligible for square-based colony count estimation of coliforms with air bubbles (h) directly plated assumed overgrown (150 CFU/1 mL). 36
Figure 23. Households interviewed in the settlement [60]..38
Figure 24. Palmolive Aquarium soap was found in the local store in Itilleq, in September 2024. 39
Figure 25. Experimental setup on (a) schematic drawing (made using Autodesk AutoCAD 2024) and (b) in real life. 40
Figure 26. Experimental lines with feed waters, temperatures and membrane pre-seeding conditions (made using Autodesk AutoCAD 2024). 40
Figure 27. Nematodes in raw water from (a) Sisimiut and (b) Itilleq. (c) Collected sample with (d) nematodes used for (e) pre-seeding membrane by injecting the sample into the silicone tubing marked with red arrow. 41
Figure 28. Greywater collection...41
Figure 29. (a) Pipe, (b) hose and (c) pots were encountered in the water springs area in Itilleq (taken by Chloe Kiernicki)..45
Figure 30. Taphouses in Itilleq: (a) taphouse 1 at the groundwater intake, (b) taphouse 2 in the center of the settlement, (c) taphouse 3 at the harbour and (d) taphouse 4 near the school, September 2024. 45
Figure 31. Water collection: (a) rinsing jerrycan, (b) wheelbarrow with jerrycans (c) for uphill transport (pictures taken by Chloe Kiernicki)......................................46
Figure 32. Household storage: (a) tank (photo by Chloe Kiernicki), (b) jerrycans stored outside, (c) jerrycans left outside and (d) growth in the jerrycan, September 2024. 46
Figure 33. Examples of washbasins: (a) in the kitchen sink, (b) in the bathroom, (c) temporary stored water in the bathroom sink, September 2024. 47
Figure 34. Heterotrophic Plate Count at 37°C in water samples collected from (a) the water distribution system and (b) household storage in Itilleq (data in Table A1, Appendix A). The detection limit was 1 CFU/1 mL (0 log CFU/mL), shown as a dotted horizontal line. Non-detects are shown as ½ of the detection limit (-0.301 log CFU/1mL). The short full horizontal line indicates means within each water source...48
Figure 35. Total coliforms in water samples collected from (a) the water distribution system and (b) household storage in Itilleq (data in Table A1, Appendix A). The detection limit was 1 CFU/100 mL for drinking water and 1 CFU/1 mL for handwash greywater (0 log CFU/mL), shown as a dotted horizontal line - this is also a guideline value for drinking water quality. Greywater results were converted from CFU/1 mL to CFU/100 mL to enable one-graph display. Non-detects are shown as ½ of the detection limit (-0.301 log CFU/100mL). The short full horizontal line indicates means within each water source…............49
Figure 36. Water pH at temperature in °C and turbidity in NTU from sampling point in (a) the distribution system and (b) from the handwashing hardware with the number of samples (N) in each category shown at the top of the chart (data in Table A2, Appendix A). Note turbidity y-axes…...50
Figure 37. Handwashing stations: (a) without and (b) with greywater recycling [60]. ...51
Figure 38. Clean membrane flux with deionized water in LMH over 24 hours in temperatures of 5.0°C, 12.5°C and 20.0°C (data for day 0 in Table B1 & Table B2, Appendix B)...54

Figure 39. Permeate flux in LMH and hydraulic resistance of the fouling layer in m^{-1} over time for all experimental lines. Note different y-axis for setups fed with greywater and tap water (data in Table B1-Table B4, Appendix B). 55
Figure 40. Top pictures of the biofilm developed on the same membranes with the respective flux in LMH for each experimental line on the 7^{th}, 14^{th} and 21^{st} day of operation (data in Table B1 & Table B2, Appendix B). 56
Figure 41. Heterotrophic Plate Counts at 22°C in feed water and permeate samples collected from setups with greywater at (a) 5°C, (b) 12.5°C, (c) 20.0°C and (d) from control with tap water (data in Table B5, Appendix B). The detection limit was 1 CFU/1 mL, shown as a dotted horizontal line. The guideline value of 200 CFU/1 mL (2.3 log CFU/1 mL) is shown as a red dashed line. Non-detects are shown as ½ of the detection limit (-0.301 log CFU/1 mL). 58
Figure 42. Total coliforms in feed water and permeate samples collected from setups with greywater at (a) 5°C, (b) 12.5°C, (c) 20.0°C and (d) from control with tap water (data in Table B6, Appendix B). The detection limit was 1 CFU/1 mL for setups fed with greywater and 1 CFU/100 mL for the setup fed with tap water, shown as a dotted horizontal line - this is also a guideline value for drinking water quality. Results from setups with greywater were converted from CFU/1 mL to CFU/100 mL to enable graph comparison. Non-detects are shown as ½ of the detection limit (-0.301 log CFU/100mL). 59
Figure 43. Water pH at temperature in °C and turbidity in NTU of (a) feed water and (b) permeate with the number of average measurement values (N) in each category shown at the top of the chart (data in Table B7, Appendix B). Note turbidity y-axes.. 60
Figure 44. Turbidity removal rates in % for each experimental line (data in Table B7, Appendix B). 61
Figure 45. Total organic carbon in mgC/L for each experimental line before and after enrichment with phosphorous (data in Table B8, Appendix B). The red dashed horizontal line indicates the raw handwash greywater level from Ziemba et al., 2018 [61], and the red full horizontal line indicates the treated handwash greywater level from Reynaert et al., 2020 [69]. 61
Figure 46. SWOT analysis for biologically activated gravity-driven membrane technology (made in Miro)... 63
Figure 47. Disinfection scenarios: (a) boiling (from Pisiffik website [81]), (b) chlorine tablets (from the Sisimiut Outdoor website [82]), and (c) UV-C LEDs (from the producer's catalogue, Appendix D). 65
Figure 48. Scenario scores for each disinfection scenario normalized within dimensions of sustainability with respect to the maximum scorable value...................... 68

List of Tables

Table 1. Quality requirements for selected microbiological parameters of drinking water. Parameters 1 and 2 are measured always, while parameter 3 only in the extended control [50]. 25
Table 2. Quality requirements for selected chemical parameters of drinking water [50]. 25
Table 3. Nutrient requirements [61]. 39
Table 4. Handwash greywater inputs [61]....39
Table 5. Dynamic water viscosity at a given temperature [77]. 42
Table 6. Elemental composition of handwash greywater inputs [61]. Individually collected data are highlighted in red. 52
Table 7. Contribution of individual inputs to handwash water composition. 52
Table 8. The final estimated composition of greywater in Sisimiut, Itilleq and Lyngby..53
Table 9. The balancing requirements for estimated composition of greywater in Sisimiut, Itilleq and Lyngby. Deficient element concentrations are highlighted in red...53
Table 10. P-values from Wilcoxon Signed-Rank Test. 54
Table 11. Social criteria. 64
Table 12. Economic criteria. 64
Table 13. Environmental & technological criteria. 64
Table 14. Pairwise comparison of criteria. Criteria with the five highest weights are bolded....65
Table 15. Values with units (1, 7, 9, 10, 13 & 14) or scores in 3-2-1/1-2-3 scale (2-6, 8, 11 & 12) for criteria evaluation. Beneficial criteria (1, 3-5 & 14) are marked with green. Non-beneficial criteria (2, 6-13) are marked with red. 67
Table 16. Criteria evaluation based on their contribution to each scenario on 3-2-1 scale. 67
Table 17. The decision matrix with final scores for each disinfection scenario in bold. The highest score is marked in red. 68

Table A1. Microbial water quality parameters for samples from Itilleq, including results below the detection limit (BDL). 77
Table A2. Physico-chemical water quality parameters for samples from Itilleq. 78

Table B1. Membrane fluxes in LMH over time. Part 1 out of 2. 80
Table B2. Membrane fluxes in LMH over time. Part 2 out of 2. 80
Table B3. Fouling layer hydraulic resistances in m^{-1}over time. Part 1 out of 2. 81
Table B4. Fouling layer hydraulic resistances in m^{-1}over time. Part 2 out of 2. 82
Table B5. Heterotrophic Plate Count at 22°C in samples from each experimental line, including results below the detection limit (BDL). 82
Table B6. Total coliforms in samples from each experimental line, including results below the detection limit (BDL)....83
Table B7. Physico-chemical water quality parameters for samples from each experimental line with the mean value, ± standard deviation and number of samples (n). 83
Table B8. Total Organic Carbon in permeate samples from each experimental line. ...83

Abbreviations

AMAP Arctic Monitoring and Assessment Programme

ATV All-Terrain Vehicle

BDL Below the detection limit

CFU Colony-Forming Unit

DBP Disinfection-By-Products

DTU Technical University of Denmark

Eawag Swiss Federal Institute of Aquatic Science and Technology

FRC Free Residual Chlorine

FU Functional Unit

GAC Granular Activated Carbon

GDM Gravity-Driven Membrane

GEUS Geological Survey of Denmark and Greenland

HPC Heterotrophic Plate Count

ICP Inductively Coupled Plasma

LED Light-Emitting Diode

LMH Liters per square Meter per Hour

LRV Log Removal Values

NTU Nephelometric Turbidity Units

O&M Operation & Maintenance

PoU Point-of-Use

RO Reverse Osmosis

SDG Sustainable Development Goal

TMP Transmembrane Pressure

TNTC Too Numerous To Count

TOC Total Organic Carbon

UF Ultrafiltration

UV Ultraviolet

WASH Water, Sanitation, and Hygiene

WHO World Health Organization

WTP Water Treatment Plant

1 Introduction

1.1 Background

1.1.1 Arctic Region

The Arctic Region stretches over northern parts of North America, Europe, and Asia, as well as the surrounding oceans and seas [1].

The Arctic and Northern Territories extend across eight countries and nations [2]:

- Canada (incl. Northwest Territories, Nunavut, Yukon),
- Finland (Northern Ostrobothnia, Kainuu, Lappi),
- Iceland,
- Norway (Nordland, Troms and Finnmark, Svalbard and Jan Mayen),
- The Russian Federation (incl. Murmansk region, Nenets, Yamal-Nenets, Chukotka Autonomous Okrugs, Komi Republic),
- Sweden (Västerbotten County and Norrbotten County),
- The Kingdom of Denmark (Greenland and Faroe Islands),
- The United States (Alaska).

In 2004, the total Arctic population was estimated to be four million with an average indigenous people share of 10% (varying from over 4% in the Arctic regions of Russia to over 88% in Greenland) [3].

The multinational nature of the Arctic Region led to numerous political or administrative considerations not previously covered when defining its area by physical, geographical or ecological characteristics [1].

Therefore, when the Arctic Council – the leading intergovernmental forum established in 1996 promoting cooperation in the Arctic [4] – started a working group of the Arctic Monitoring and Assessment Programme (AMAP), the circumpolar region was defined. It includes terrestrial and marine areas north of the Arctic Circle (66°32'N), north of 62°N in Asia and 60°N in North America, modified to include the marine areas north of the Aleutian chain, Hudson Bay, and parts of the North Atlantic Ocean including the Labrador Sea (Figure 1) [1].

Figure 1. The boundary of the Arctic Monitoring and Assessment Programme area with the Arctic marine boundary, Arctic circle and 10°C July isotherm ([1], edited by author).

In the circumpolar region, typical **cold climate challenges** are faced in various locations, including the areas of **Greenland**.

1.1.1.1 Cold Climate Challenges

The Arctic Region is characterized by **low air temperatures** (from -30 to -35°C in winter and from 0 to 2°C in summer in the central Arctic). They are caused by a smaller amount of solar radiation received in the Arctic locations than in the rest of the world annually. This is due to the lack of sun in the winter months and an ongoing reflection of the great share of radiation by extensive cloud, snow and ice cover – also during the summer, when solar radiation is the highest on Earth [1].

Air temperature is one of the contributors to the **permafrost** formation. Permafrost, a perennially frozen ground, is a soil, bedrock or organic matter staying at or below 0°C for at least two consecutive summers. Its occurrence depends on elevation and ground characteristics. In the coldest areas of the Arctic, permafrost may reach depths of 600-1,000 m underneath as little as several centimetres of active layer. The active layer is the upper layer of soil that thaws during the summer and in the southern, dry areas may reach a few meters of depth. Repeated freezing and thawing enable frost actions, resulting in characteristic surface features such as frost scars and the **unstable active layer** [1].

Frozen, liable to melt ground, low temperatures and long hours of darkness are some of the factors limiting the capacity of designing, constructing and maintaining **infrastructure** in the Arctic [5]. The development of infrastructure is also affected by the higher financial costs of applying advanced engineering solutions that are suitable for extreme climate conditions. Lack of infrastructure such as roads affects transportation within the region. Some locations can be reached only by air, seaway or seasonal ice roads [6]. Their remoteness often results in limited supplies (e.g. food, materials or energy) and capacity issues on the community level negatively affecting access to services (even such as education and healthcare). Living modern life in **remote communities** is already very challenging, making them even more vulnerable to other threats, including the ones from climate change [7].

Global climate change affects Arctic communities more than ever. Rapid, transformational changes in ecosystems negatively impact health and well-being, food security, transportation, livelihoods, industries, infrastructure, and the availability of safe drinking water [7]. To build the resilience of Arctic people, action must be taken on both, global and local levels, with the engagement of all countries with Arctic nations – including Greenland.

1.1.1.2 Greenland

Greenland (*Kalaallit Nunaat* in the official language *Kalaallisut* - Greenlandic), a former Danish colony, is an autonomous territory of the Kingdom of Denmark with the capital in Nuuk. Despite its cultural belonging to Europe, Greenland is geographically located in North America [8]. The total area of 2,200,000 km^2 makes Greenland the biggest non-continental island in the world (Figure 2). The highest population density is on the coastline, where in 2024, 56,699 Greenlanders lived in 17 towns and 55 settlements administrated by 5 municipalities – Avannaata, Kujalleq, Qeqertalik, Qeqqata and Sermersooq. With 88% of the population living in the urban areas, towns have an average of 2,937 inhabitants (from 363 in Ittoqqortoormiit to 19,872 in Nuuk, both in the Sermersooq Municipality). 11.8% live in rural Greenland with an average population of 122 per settlement (from 2 in Ikerasaarsuk, Avannaata Municipality to 517 in Kangerlussuaq, Qeqqata Municipality). The remaining 0.2% lives outside towns and settlements – either on stations or their residence is unknown. Populations of urban (towns) and rural (settlements) areas in the whole country and in each municipality are presented in Figure 3. Towns usually serve as regional hubs for surrounding settlements, offering essential administrative, healthcare, educational, and commercial services [9], as in the case of Sisimiut and Itilleq from Qeqqata Municipality.

Figure 2. Map of Greenland with the location of Sisimiut and Itilleq (made in QGIS version 3.22 using OpenStreetMaps [10]).

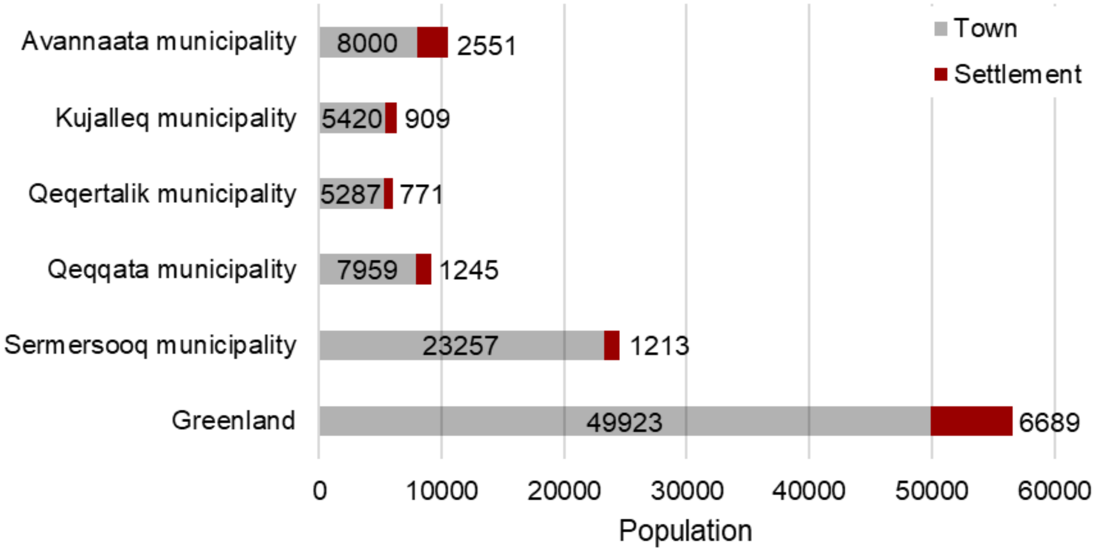


Figure 3. Distribution of the population in urban and rural areas of the Greenlandic municipalities (data for 2024 from StatBank Greenland [11]).

Greenlandic Town - Sisimiut

Sisimiut (Figure 4), with a population of 5,412 [11] is not only the administrative centre of Qeqqata municipality but also the second-biggest Greenlandic town. It is located 42 km north of the Arctic Circle by the small Kangerluarsunnguaq Bay [12] and can be reached all year round by air, as it has its own airport, or by seaway to its non-freezing harbour. There is also a rough ATV track from Kangerlussuaq used with snowmobiles and dog sledges in the season, as well as a route for hiking on the southern Arctic Circle Trail [13].

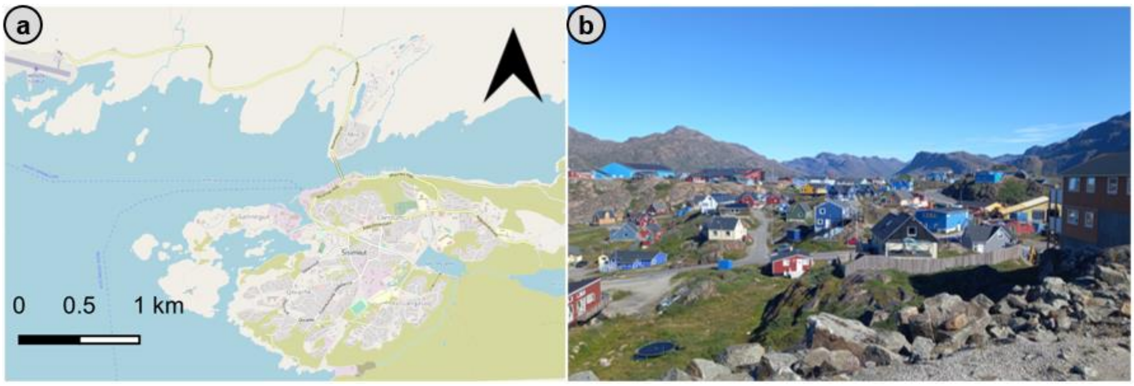


Figure 4. Sisimiut (a) on a map (made in QGIS version 3.22 based on data from OpenStreetMap [10]) and (b) in real life, August 2024.

In the town, public **transportation** by bus along with private taxi drives are available [13]. **Healthcare** services are provided at the regional hospital. Despite its focus on outpatient care, a 19-bed ward and operating theatre with a delivery room can be found in town [14]. **Education** is given at two primary schools and at various general and vocational schools such as KTI - Tech College Greenland (Greenlandic name is *Kalaallit Nunaanni Teknikimik Ilinniarfik*) offering technical high school (GUX) and other programmes on construction and engineering, raw materials and languages. It is also possible to pursue a higher education in Arctic Civil Engineering or Fisheries Technology at the Arctic DTU in Sisimiut managed by the Technical University of Denmark in collaboration with KTI [15]. Various **stores** are located in Sisimiut, including supermarkets Brugsen, Spar, Akiki or Pisiffik as well as the fresh food market Qimatulivik [16]. Great opportunities for **social activities** are offered in different clubs, e.g. Sannavik for people with disabilities or Nutaraq for the youth [17], in the Sisimiut Museum, Culture Center Taseralik (with cinema, theatre and cafe) and in the Sports Hall with fitness centre. Other locations like Starlight, Bilardklubben, Kukkukooq Bar or Raja Bar can be visited for live music or DJ disco experiences. Restaurant Nasaasaaq, Café Jasmine, Café Sisimiut, Café Ulu or Nanas Thai Take Away are some of the food venues operating in town [16]. The largest industry in Sisimiut is public administration and service (education and healthcare included), followed by fish industry, trade and automotive repair, construction and transport with growing tourism. Additionally, the headquarters of the Greenlandic housing company INI A/S and supply company KNI A/S with its subsidiaries including Pilersuisoq – the largest retail chain in Greenland - are located in Sisimiut [18].

Greenlandic Settlement - Itilleq

Itilleq (Figure 5) is one of the settlements in the Sisimiut district of Qeqqata municipality, situated approximately 45 km south of the town on the island with the same name [19]. A population of 86 inhabitants [11] makes it a good example of an average Greenlandic settlement. **Transportation** to Itilleq takes approximately 1 hour from Sisimiut by seaway - there is a boat bridge and quay facility in the settlement's harbour used regularly by supply ships, charter tours or private boats [19]. With a helistop on the island, the settlement is also accessible by air [20].

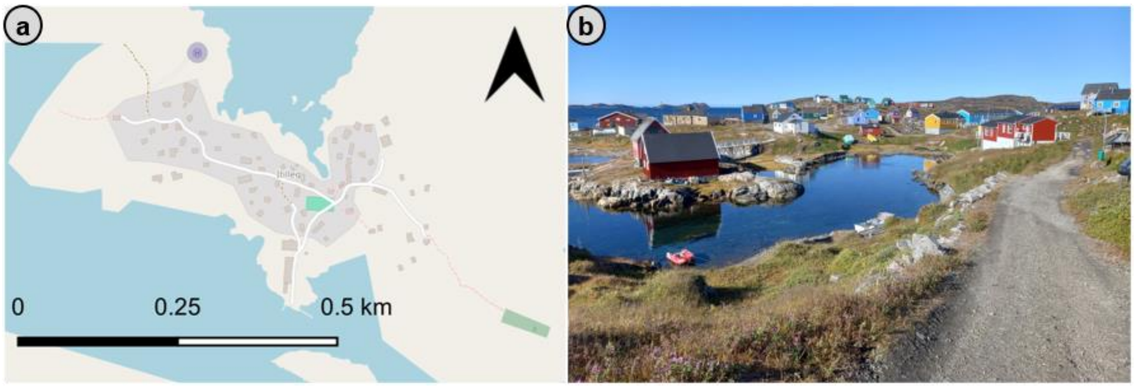


Figure 5. Itilleq (a) on a map (made in QGIS version 3.22 based on data from OpenStreetMap [10]) and (b) in real life, September 2024.

There is a carriageway throughout the settlement with a small slope that is used for **ATV drives** and can be expanded or upgraded in the future, there are also plenty of pathways to walk on the island. The **local municipal office** can be found in the centre of the island, next to the service house (bathing and laundry facility in the community) and nursing station where healthcare services are provided during medical visits in the settlement. There are two **educational institutions** – kindergarten and primary school. In addition, the municipality provides various vocational courses. **Social activities** are organized in the communal building [21]. The only **supermarket** on the island is Pilersuisoq located next to a Royal Greenland **fish factory** – another workplace on the island [22].

The situation in Itilleq highlights the characteristics of Greenlandic settlements, with small population sizes and remote locations limiting access to infrastructure and services, especially in the critical **Water, Sanitation, and Hygiene (WASH) sector**.

1.1.2 Water, Sanitation and Hygiene (WASH)

1.1.2.1 WASH Barriers to Disease Prevention

The importance of WASH services is directly linked to human health with both, long-term consequences, such as heavy metal poisoning, and short-term effects, including infectious diseases that require immediate response.

WASH-related diseases can be grouped into (Bradley's classification, [23]):

- **Waterborne diseases** caused by pathogens (bacteria, viruses, protozoa and helminth) in contaminated water,
- **Water-washed diseases**, such as skin, eyes or diarrhoeal diseases arising from insufficient water for personal hygiene,
- **Water-based diseases** caused by parasites relying on aquatic intermediate hosts, entering the human body through skin contact or ingestion,
- **Water-related insect vectors of diseases**, where insects breed in water or live near the fetching point.

To address various infectious agents and routes of disease transmission, it is essential to implement effective **WASH barriers**, including [24]:

- Separating faeces from water sources and the environment,
- Ensuring safe drainage systems,
- Protecting and maintaining water sources,
- Treating, conveying, and storing water safely,
- Enabling and promoting personal hygiene practices like hand washing and bathing.

1.1.2.2 Human Rights and Sustainable Development Goals

Due to its contribution to human health, dignity and overall prosperity, water and sanitation were recognized by the United Nations as **human rights** [25] with direct translation into the Sustainable Development Goals (SDGs, Figure 6) to be achieved by 2030 [26]. Even though different SDGs can be found relevant for the WASH sector, it is mainly covered by **SDG6, "Safe water and sanitation"** which aims to "ensure availability and sustainable management of water and sanitation for all" by:

- Safely managed drinking water and sanitation services,
- Handwashing facilities with soap and water,
- Safely treated domestic wastewater flows,
- Increased water-use efficiency.

Since SDG6 targets and indicators remain very general [26], further specification by various guidelines and standards is required.

Figure 6. UN Sustainable Development Goals logo with the icon of SDG6 (materials edited by the author [27]).

1.1.2.3 Guidelines and Standards on Access to WASH-services

General advice and best practices can be found in the guidelines delivered by the World Health Organization (WHO) for drinking water quality [28], sanitation and health [29], and hand hygiene in health care [30]. These guidelines are often the basis for developing local legislation, for example in Greenland. They were also incorporated in WASH standards for long-term humanitarian settings set by Sphere [24] to:

- ≥ 15 litres of water for drinking and domestic hygiene per person per day,
- Minimum water quality: no coliforms in 100 mL, turbidity < 5 NTU, Free Residual Chlorine (FRC) in chlorinated water 0.2-0.5 mg/L,
- ≤ 5% of household income spent on water for drinking and domestic hygiene,
- ≥ 1 toilet with a handwashing station per 5 people or 1 family,
- ≥ 1 bathing facility (e.g. shower) for 20 people, ≥ 1 laundry facility for 100 people.

1.1.2.4 WASH Sector in Greenland

Legal Framework

The WASH sector in Greenland is primarily regulated by the **Environment Protection Act** (Danish name: *Inatsisartutlov nr. 9 af 22. november 2011 om beskyttelse af miljøet*) established by the Parliament of Greenland in 2011. This act applies to the land territory and land-based marine pollution, ensuring sustainable development with respect to nature through:

- Protecting population health,
- Preventing and minimizing pollution,
- Limiting the use of resources and promoting recycling.

Regulations on drinking water and waste found in the Environment Protection Act (chapters 6 and 7 respectively) are developed in greater detail in the executive orders of the Parliament of Greenland (or before 2008 Greenland's Home Rule) on:

- **The Protection of Freshwater Resources and the Extraction of Freshwater for Drinking Water** (Danish full name: *Hjemmestyrets bekendtgørelse nr. 9 af 15 april 1993 om beskyttelse af ferskvandsressourcer og indvinding af ferskvand til drikkevand*),
- **The Disposal of Latrine and Wastewater** (Danish full name: *Selvstyrets bekendtgørelse nr. 10 af 12. juni 2015 om bortskaffelse af latrin og spildevand*),
- **The Water Quality and Supervision of Water Supply Facilities** (Danish full name: *Selvstyrets bekendtgørelse nr. 63 af 4. november 2021 om vandkvalitet og tilsyn med vandforsyningsanlæg)*.

These directives have a direct impact on the organization of sanitary services and water supply in Greenland, with more details further specified in:

- **County Council Act on Subsidies for the Establishment of Service Houses in Settlements** (Danish full name: *Landstingslov nr. 9 af 16. November 1984 om tilskud til etablering af servicehuse i bygder*),
- **Parliament Act on the Greenland Home Rule Government's Takeover of Settlements' Electricity and Water Supply** (Danish full name: *Landstingslov nr. 13 af 6. november 1997 om Grønlands Hjemmestyres overtagelse af bygders el- og vandforsyning*),
- **County Council Ordinance on Water Supply** (Danish full name: *Landstingsforordning nr. 10 af 19. November 2007 om vandforsyning*).
- **Parliament's Law on Land Development, Public Sewers and Public Roads** (Danish full name: *Inatsisartutlov nr. 19 af 17. November om byggemodning, offentlige kloakledninger og offentlige veje*).

Water Supply

a) Water Utility - Nukissiorfiit

The Greenlandic utility is called Nukissiorfiit. It is owned by the Self-Government of Greenland and reports to the Ministry of Agriculture, Self-sufficiency, Energy and Environment [31]. Nukissiorfiit is divided into six regions - Avannaa, Ilulissat, Disco, Qeqqa, Nuuk, and Kujalleq (Figure 7a, [32]) covering all towns and 54 settlements (2024). Depending on the location, Nukissiorfiit supplies electricity, water, heat or all of these [33]. Utility is also responsible for carrying out the nationwide planning of water supply in cities and settlements [34]. There are 73 waterworks managed by Nukissiorfiit [33] and their average annual water production oscillates around 5 Mm^3 with 5.49 Mm^3 supplied in 2023 (Figure 7b). Only around 37% is consumed by households and the remaining 63% is demanded by various industries incl. manufacturing [35]. Water production costs differ between locations as presented in Figure 8.

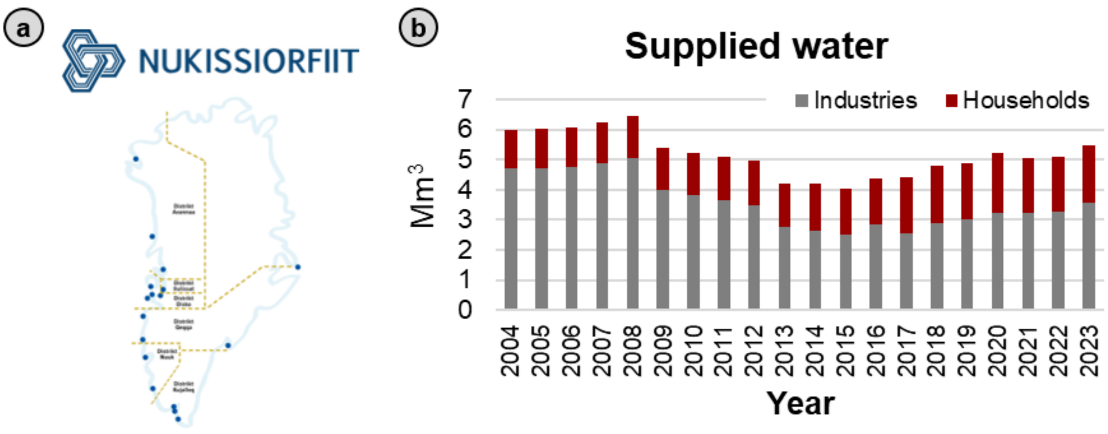
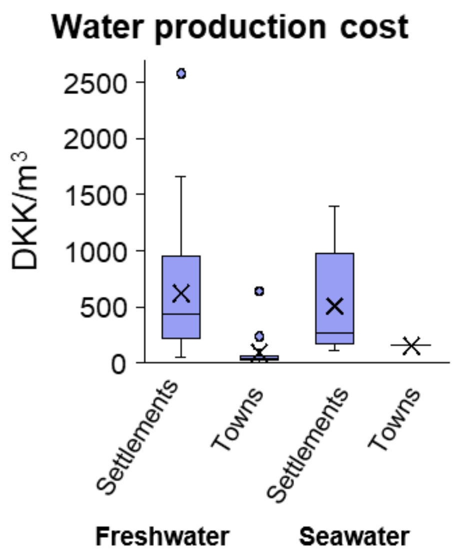


Figure 7. (a) Logo and regions of Nukissorfiit [31] with (b) the volumes of supplied water for households (red) and industries (grey) in Mm³ over the years 2004-2023 (data from StatBank [35]).

There is no clear relationship between water source and water production cost as it seems to be more dependent on the location. On average, settlements have higher values than towns - 6.75 times higher for freshwater and 3.26 times higher for seawater.



For example, in Itilleq it's 1,394.19 DKK/m³, while in Sisimiut it's 9.51 DKK/m³. This is the result of fixed operation rates split over a relatively small water volume meeting the domestic demand in settlements [33]. Despite those differences in production cost between locations, supplied water in the whole country is charged in a one-price system (21.95 DKK/m³ in 2025) set by the Self-Government of Greenland, with special discount prices for the fish industry [36].

Figure 8. Water production cost in DKK/m³ for settlements and towns (Nukissiorfiit data [33]) divided by their water sources (data from Jupiter database [37]).

There are only four towns (Ilulissat, Sisimiut, Nuuk and Aasiaat) where the state price for water is higher than the cost of production [33]. However, since these locations are home to 59% of the Greenlandic population [11], it may bring some balance to the utility's revenue. Even though water sources may not affect water production prices to the same extent as sharing costs over a small population, they remain the basis for choosing treatment technology - the heart of water supply.

b) Organization of Water Supply

Water Sources

There are a few locations with small populations, such as settlements Naajaat and Nutaarmiut in Avannaata municipality [38], [39], where water supply is not provided. Probably due to the cold climate and economic limitations, residents themselves fetch freshwater or melt ice floes in the winter season. Glacier ice melting is also used in the town of Qaanaaq during four months of winter after reservoirs filled with river water have been drained [40]. Despite complete seasonal reliance on ice melting in Qaanaaq, since the water for the rest of the year originates from the river, the Geological Survey of

Denmark and Greenland (GEUS) classified the town's water source as **freshwater** - the most common water source in Greenland, also used in Sisimiut (Figure 9a). If lake or river water is not available, in some locations, like Itilleq, shallow groundwater originating from **infiltration** is extracted (Figure 9b) [37]. When there is no alternative, sometimes **seawater** (Figure 9c) may be used in water production through the process of water desalination. To minimize the risk of contamination at the water source, protection zones are established around intakes [41].

Figure 9. Intakes of (a) lake water in Sisimiut, August 2024, (b) groundwater and (c) seawater in Itilleq, September 2024.

Water Treatment

After extraction, water is treated at the water treatment plant (WTP) in the processes designed based on the raw water quality. Typically, the water undergoes:

- **Aeration** - bringing water in contact with air to remove unwanted gases and volatile compounds and oxidize soluble compounds of iron and manganese to their insoluble precipitates [42],
- **Sand filtration** - passing water through sand or other filter material to remove suspended solids and soluble compounds [42],
- **UV treatment** - applying ultraviolet light to inactivate pathogenic organisms in water [43],
- **Chlorination** - dosing chlorine to inactivate pathogenic organisms in water and provide ongoing protection [43],
- **pH correction** - bringing pH closer to the neutral level of 7 by either filtrating water through alkaline, e.g. lime-based, medium or by adding sodium compound [41].

When **advanced water treatment** is needed, this may involve the following processes:

- **Clarification** - removing suspended solids through their destabilization by charge neutralization (coagulation), agglomeration of created flocs (flocculation) and physical removal of coagulated and flocculated particles with the sludge (sedimentation) [42],
- **Activated carbon filtration** - passing water through activated carbon (usually granular activated carbon, GAC) to remove chemical contamination from water [42].

In the case of **seawater desalination**, water treatment additionally includes:

- **Reverse osmosis (RO)** - removing a significant portion of dissolved solids and other contaminants, including chloride ions, by forcing water through a semi-permeable membrane [44],
- **Akdolit filtration (water remineralization)** - replenishing the permeate from reverse osmosis with vital minerals by filtrating water through lime-based filter material [45].

Water in Sisimiut is treated using aeration, sand filtration (Figure 10a), UV treatment, and chlorination with pH correction (Figure 10b). Itilleq on a regular basis has a similar treatment train, with the absence of aeration and chlorination, but at the WTP (Figure 10c) seawater desalination is also possible. Waterwork in the settlement is built from modules designed by Krüger specifically for the Greenlandic conditions. Therefore, there is also a constant monitoring of pH, conductivity and turbidity reported back to Nukissorfiit [46].

Figure 10. (a) Sand filters and (b) NaOCl dosing station at the Sisimiut WTP, August 2024. (c) View to the inside on the Itilleq WTP, September 2024.

Water Conveyance

Water is distributed using **pressurized pipes** - directly to taps of consumers or to **taphouses**, from which residents can haul water (Figure 11a). In some areas that are not connected to the water supply network, water may be delivered to tanks in the buildings with **water trucks** (Figure 11b). However, due to the high cost of operation, this method is not preferred [47]. Because of the extreme climate conditions, building a pipeline is a big challenge. It is not uncommon to encounter with **pipes built above the ground**, as when they are buried in the active layer, they may be affected by the ground movement, and when they are deeper in the ground, maintenance and repairs become more complex. Arctic pipes have **insulation** and usually **freeze prevention,** e.g., a heating system [48]. In Sisimiut, there are only a few homes in the older residential areas that still get water from taphouses. The rest is supplied through pipes and some by the water truck. On the other hand, in Itilleq, only a few buildings such as the service house, kindergarten, school or community building are piped. With no water truck service, all residents must rely on four taphouses located in different parts of the island (Figure 12).

Figure 11. (a) Heated pipes above the ground supplying taphouse in Itilleq, September 2024. (b) Filling of the water truck at the water treatment plant in Sisimiut, August 2024.

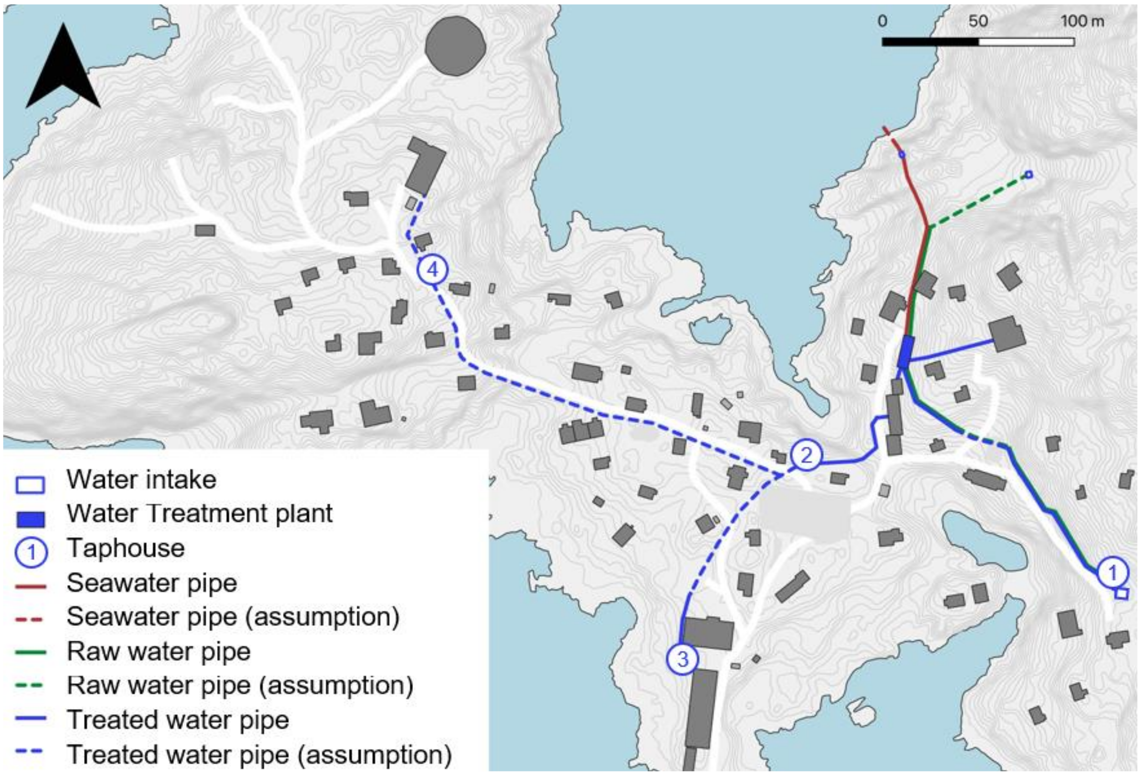


Figure 12. Water supply in Itilleq (made in QGIS version 3.22 based on data from Asiaq Map Supply Service [49] and OpenStreetMap [10]).

Water Quality Requirements and Control Frequencies

Taps, water tanks and taphouses are among the locations where microbiological and chemical parameters of water quality (Table 1 and Table 2 respectively) must be met. Water is analyzed on a regular basis with a minimum number of measurements depending on the water production [50]. In practice, there are 1-2 samples every month in towns and 1 every year in settlements [41]. Taphouse or tap is also, where the responsibility of the water supply operator ends [50].

Table 1. Quality requirements for selected microbiological parameters of drinking water. Parameters 1 and 2 are measured at all times, while parameter 3 is only in the extended control [50].

Nº	Parameter	Requirement	Comment
1.	Coliform bacteria	<1 CFU/100 mL	
2.	*Escherichia coli* (E. coli)	<1 CFU/100 mL	
3.	Heterotrophic Plate Count in 22°C	<50 CFU/1 mL[1], <200 CFU/1 mL[2]	[1] Outlet from the WTP. [2] Network or the tapping point.

Table 2. Quality requirements for selected chemical parameters of drinking water [50].

Nº	Parameter	Requirement	Comment
1.	pH	6.5-9.5	Exception can be granted.
2.	Turbidity	1 NTU	Exception can be granted.

Overview of Water Supply in Greenland

An overview of water sources, treatment technologies and water conveyance is presented in Figure 13.

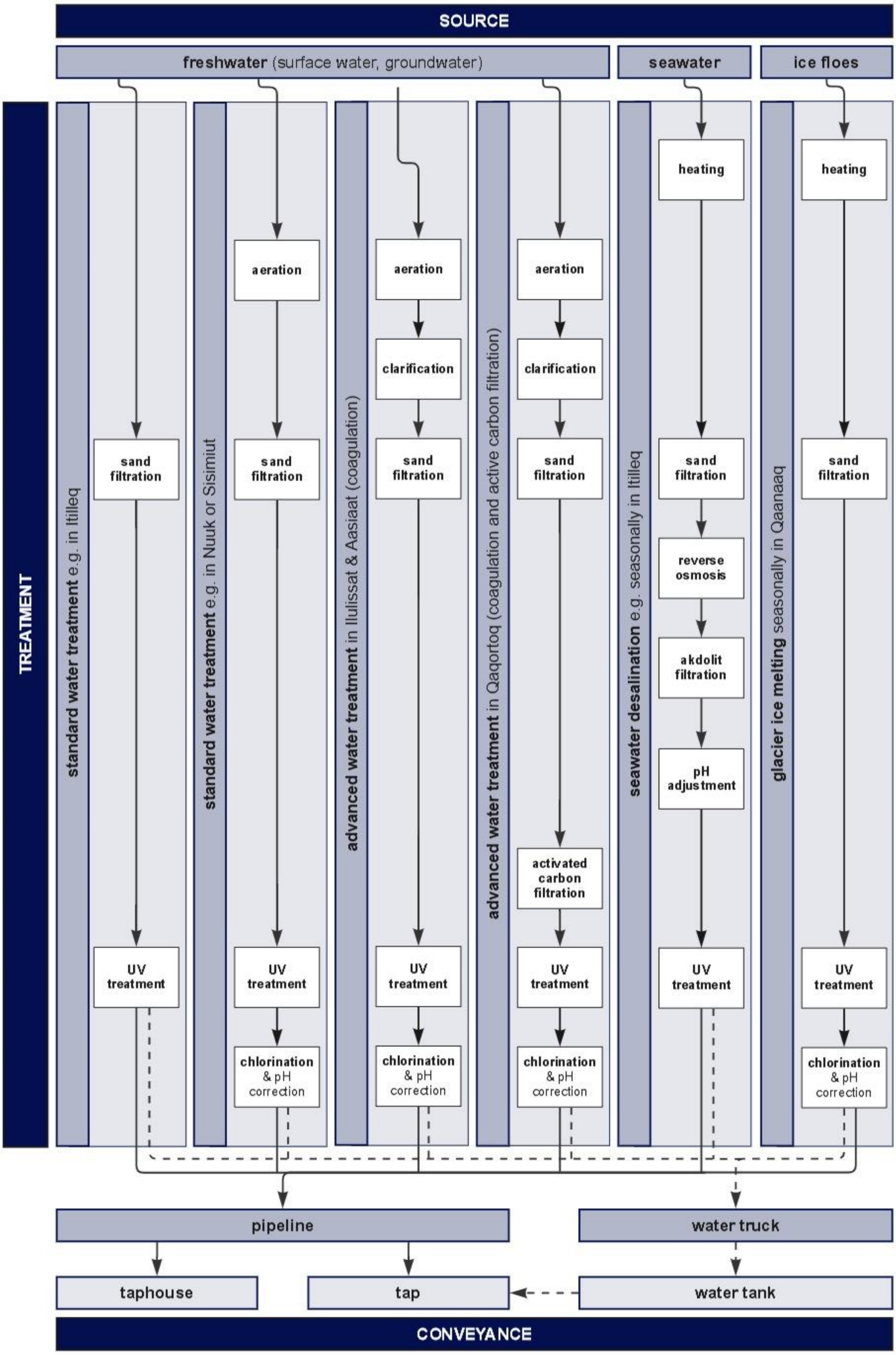


Figure 13. Overview of water supply sources, treatment technologies, and conveyance methods in Greenland (made in Miro based on data from Nukissiorfiit [41], [47]).

Sanitation and Waste

In contrast to water supply, sanitation and waste are the responsibility of municipalities [51]. Providing these services is especially challenging in remote areas, including settlements, where small populations are highly affected by the cold climate.

Waste is **openly dumped** in the designated areas until shipped for **thermal or other treatment** to Sisimiut or Nuuk, where incineration plants are operated by ESANI, the national waste management company [52]. Despite much development in the waste sector, including resource recovery, waste must always be thoroughly considered.

In the regulation on **sanitation**, the following functional groups and user interfaces are defined [53]:

- **Wastewater** - all water discharged from homes and other buildings,
- **Latrine** - human waste, urine and faeces,
- **Blackwater** - wastewater from flush toilets,
- **Flush toilet** - a toilet connected to water and wastewater system (sewer or tank),
- **Dry toilet** - a sanitary installation with no or very little water, e.g. a bag toilet,
- **Greywater** - domestic wastewater without drains from flush toilets.

a) Toilet Waste - Latrine and Blackwater

Human waste is collected using either **dry or flush toilets**. When cleaning and reuse are feasible, dry toilets may be bucket-based as they are for some households in Nuuk [54]. In other places, plastic bags are used. Once the bag in the dry toilet is filled, it is removed from the house. In some locations, e.g. Savissivik settlement in Avannaata municipality, locations, toilet user must dispose of their waste themselves. Otherwise, toilet bags are picked up with a **wheel barrel or a truck**, transported to the **latrine discharge ramp** and emptied as a “natrenovation” service organized by the municipality [55]. The only exception, bringing a lot of consideration, is the town of Qaanaaq where filled bags are stored without discharge [56].

Installation of a flush toilet requires a water supply (from a pipe or water tank) and a **sewer or septic tank** connection. After every use, human waste is flushed and either stored until pickup with a **vacuum truck** transporting it to the sewage pumping station, so-called “chocolate factory”, or directly transported in the **sewerage system** [55]. Regardless of the sanitary solution, human waste ends up in the sea **without any treatment**. It is usually discharged through outlets in locations with strong currents to enhance faster dilution [57]. An overview of sanitation systems is presented in Figure 14.

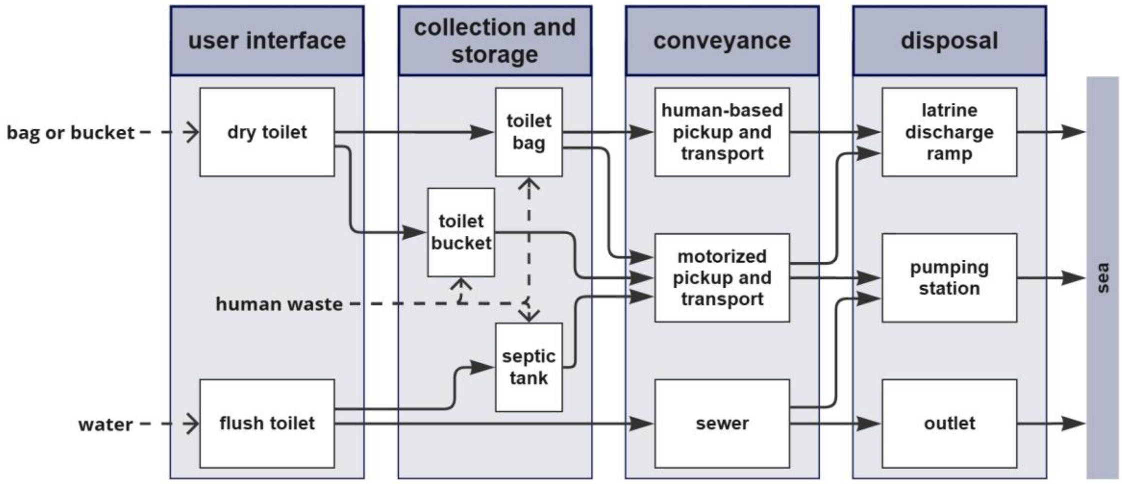


Figure 14. An overview of sanitation systems for human waste collection in Greenlandic households (made in Miro inspired by Compendium of Sanitation Systems and Technologies [58]).

In Itilleq, as in the majority of Greenland, it is not feasible to establish flush toilets. Therefore, all residents use dry toilets (Figure 15a) with bags stored outside when full (Figure 15b). They are picked up with a tractor (Figure 15c) and emptied on a latrine discharge ramp (Figure 15d,e) in a location far from the seawater intake [57].

Figure 15. Sanitation in Itilleq: (a) dry toilet in the service house, (b) bags stored outside the household, (c) tractor with a shovel to pick up the bags, (d) latrine disposal site with a sea view, and (e) latrine disposal ramp, September 2024.

In Sisimiut, as in the majority of towns, many households are connected to the sewerage discharging to the sea (Figure 16). However, there are still some locations remaining unpiped due to the high cost of the construction - residents of those areas either use septic tanks (300 households in 2020) or dry toilets (151 units in 2020) [57].

Figure 16. (a) "Chocolate factory" in Sisimiut discharging (b) wastewater into the sea, June 2023.

b) Greywater

Greywater from the household is produced from **cooking** (food washing, washing dishes), **personal hygiene** (hand washing, showering, laundry) and **cleaning** (Figure 17**)**. Sources at the location depend on the level of access to WASH services. For example, in unpiped homes, it is uncommon to encounter shower or laundry machines - they are available in the service houses established in the communities by municipalities with up to 85% of the governmental subsidy (Figure 18) [59].

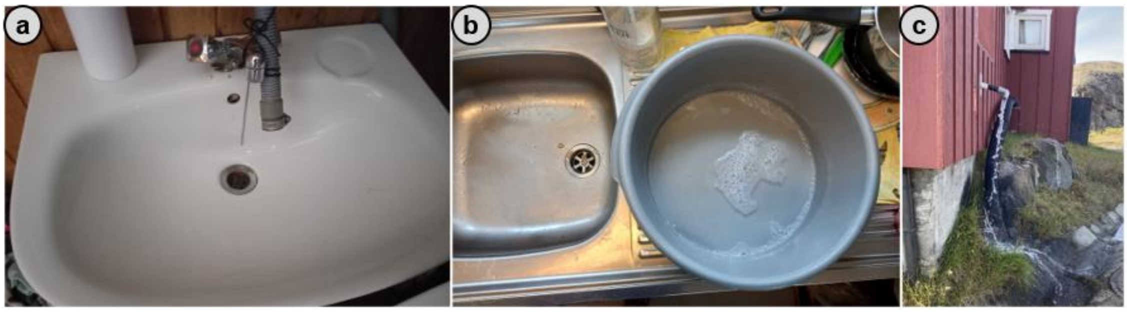


Figure 17. Greywater sources in unpiped homes: (a) bathroom sink and (b) kitchen sink with washbasin in Itilleq, September 2024. (c) Household greywater outlet in Sisimiut [60].

Figure 18. Service house in Itilleq. Greywater from (a) showers, (b) washing and (c) laundry facilities is (d) discharged to the sea through a pipe, September 2024.

Greywater is directly **discharged on the terrain** or transported by sewers **into the sea** [53]. It may be drained through **gravity pipes** or, in the case of unpiped homes, **manually dumped outside** [60]. Greywater volumes and characteristics are very source- and location-dependent. Even when quantifying the minimum water needs, water for cooking and basic personal hygiene may sum up to over 80% of the total water demand [24]. The composition of greywater is a direct result of its inputs (water, detergents and washed-off materials) and therefore may vary significantly [61].

These variations apply also to microbial contamination as it was found in the greywater runoff in Sisimiut (Figure 19). **Heterotrophic Plate Count (HPC)** is a general indicator of microbial presence in the water. Even though these bacteria may not be harmful, their content is related to the organic matter and nutrients in greywater, and therefore with a concentration in the range of $10^{0.5}$ to $10^{2.6}$ CFU/1 mL, it points to its contamination. This is also confirmed by the concentration of other microorganisms, **total coliforms**, in the range of $10^{1.7}$ to $10^{4.3}$ CFU/1 mL with possible faecal contamination indicated by the presence of $10^{0.9}$ to $10^{4.3}$ CFU/1 mL of ***Escherichia coli* (*E. coli*)** in 6 out of 9 samples [62].

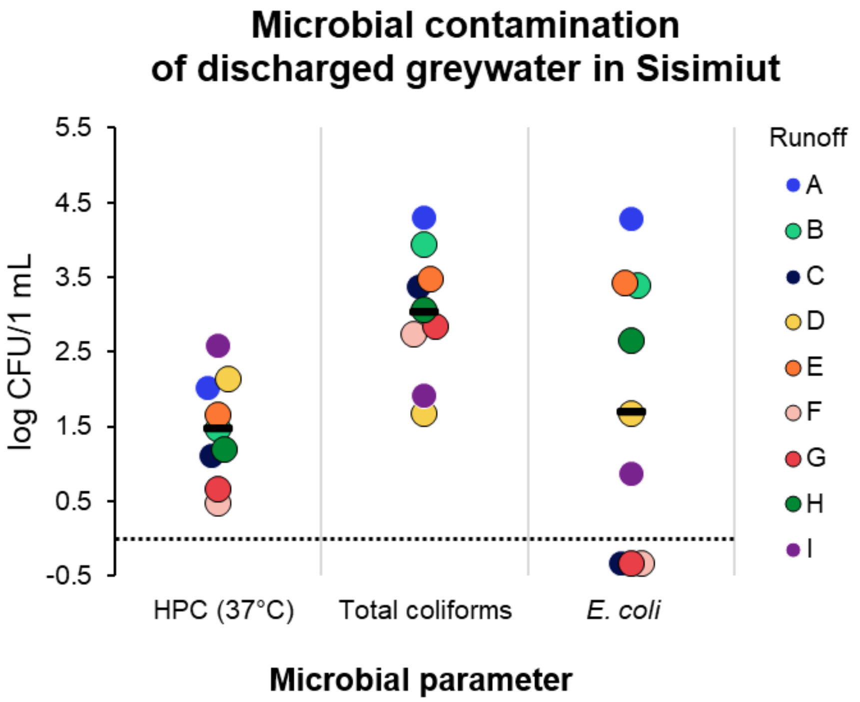


Figure 19. Average Heterotrophic Plate Count incubated at 37°C, total coliforms and E. coli in greywater samples collected from runoffs A-I in Sisimiut (data from [62]). The detection limit was 1 CFU/mL (0 log CFU/1 mL), shown as a dotted horizontal line. Non-detects are shown as ½ the detection limit (-0.301 log CFU/mL). Means within each microbial parameter are indicated by the short full horizontal line.

Previous Studies on Household Storage

Due to microbial contamination, greywater should not be used for personal hygiene or other purposes without treatment. However, according to research on drinking water sufficiency, affordability, accessibility, acceptability and safety, in 2019, there were still Greenlandic households of native rural communities living in unpiped homes, where **greywater was reused directly**, e.g. in handwash basins. Handwash basins are a water-saving practice that is based on **misconceptions** about hygiene as they intend to prevent the spread of diseases by providing family members and guests with a handwashing station. Users of handwash basins dip their hands in and rub with soapy water, to then dry them without rinsing [63].

Levels of microbial contamination in the water stored in wash basins were found to be for HPC in order of 10^2 to 10^5 CFU/1 mL and for total coliforms from absence in one sample and presence after enrichment in two to 10^5 CFU/1 mL in five samples. *E. coli* was detected in a range of 2 to 5 CFU/1 mL in 4 out of 12 samples. As the water became a **reservoir for various pathogens**, it could potentially expose users to health risks, including WASH-related diseases [63]. The presence of water storage units like washbasins in households is linked to **insufficient water quantities** classified for the visited rural communities as a basic level of water access (according to WHO categorization [64]). Relatively **small volumes of water** are carried home because of the heavy water weight, distance from the taphouse and seasonal weather conditions that make this process challenging. Insufficient water quantities lead to drinking and cooking being prioritized over hygiene [65]. **Compromised hygiene** is especially concerning because of the increased risk of contact with excreta due to the dry toilet use in the households. Since Nukissorfiit's responsibility ends at the taphouse, which is checked for microbial water quality parameters no more often than once a year and delivers unchlorinated water with no residual protection [66], there is **limited information about water quality during household storage**. All available data originates from the same independent study that acknowledged the use of washbasins as a matter of concern and recommended creating an in-home running water point for handwashing in unpiped homes [63].

An overview of the causes and effects of WASH in the Greenlandic unpiped home is presented in Figure 20.

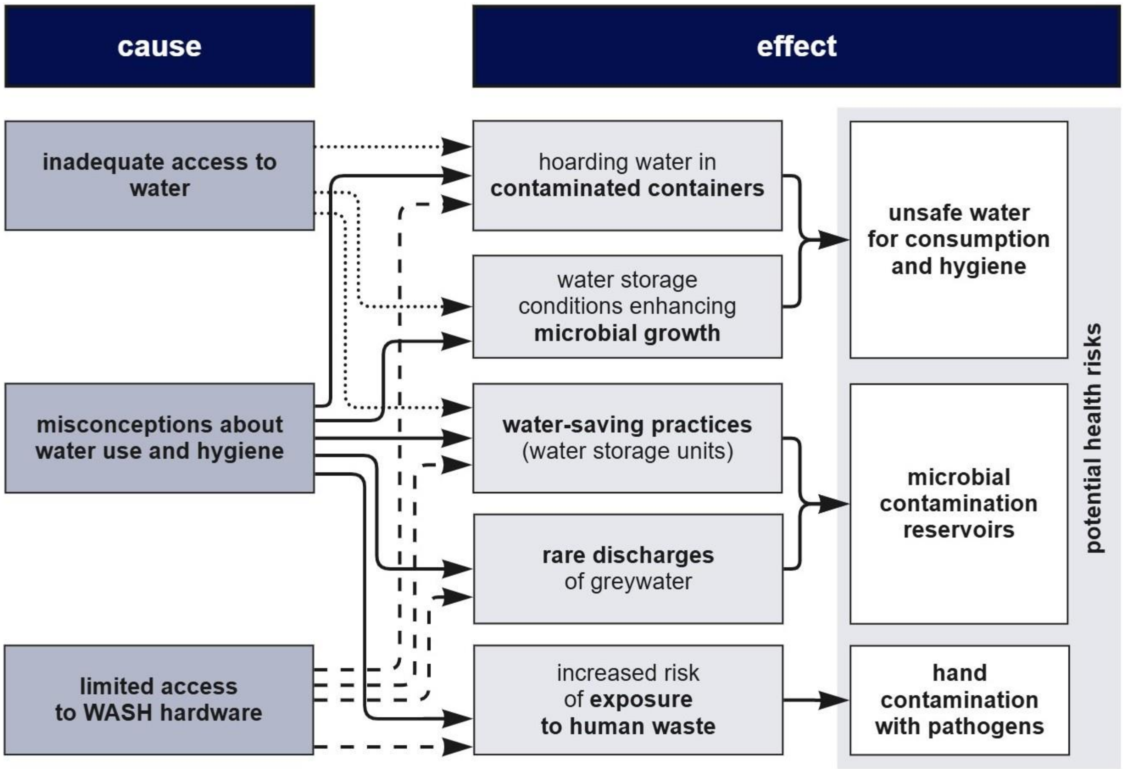


Figure 20. Cause-effect chain of WASH in the Greenlandic unpiped home (made in Miro).

Suppose handwash basins remain a common practice in unpiped homes due to the ongoing insufficient access to water. Considering the high economic cost of expanding the water network, **decentralized solutions** such as on-site treatment for same-purpose greywater reuse, so-called **greywater recycling**, should be investigated for handwashing.

1.1.3 Decentralized Greywater Recycling

While centralized treatment is done at one big facility, in **decentralized solutions** processes are performed at the locations where water is brought (water treatment) or wastewater is generated (wastewater treatment). Despite its limitations, such as a lower potential for resource recovery, a shift from one big facility to many smaller units, addresses challenges in the areas where traditional water supply or sewage networks are not feasible to expand [67].

On principle, greywater recycling is a **two-step treatment** of (1) the **main treatment** removing contamination, such as suspended solids, to ensure eligibility for (2) **disinfection** inactivating pathogens and improving microbial water quality. The choice of treatment is made based on greywater characteristics related to the source of origin. For example, greywaters from kitchen and bathroom sinks have been treated as separated streams due to different loads of nutrients and other qualities [68]. The desired quality of water at the point of use must be also considered.

For handwashing greywater, a successfully implemented on-site solution with limited maintenance was developed by the Swiss Federal Institute of Aquatic Science and Technology (Eawag) using **biologically activated gravity-driven ultrafiltration (UF) membranes** [69].

1.1.3.1 Biologically Activated Gravity-Driven Membrane Technology

Membrane separation processes are based on **feed water** filtration through a semi-permeable membrane initiated by the **driving force** and resulting in a treated product water, so-called **permeate**. The main types of **membrane modules** are flat-sheet, hollow-fiber, tubular or spiral-wound membranes. They can be operated in two different **flow modes**: dead-end, directly through the membrane surface, or cross-flow, parallel to the membrane surface. Permeate volume collected per unit area of the membrane per unit time is called the volumetric **flux**, expressed as $L/(m^2 \cdot h)$ or LMH. A decrease in the flux due to the blockage of membrane pores by the solute accumulated on the membrane surface after certain operation is referred to as **fouling**. It may be reversible (when after washing the membrane flux is restored) or irreversible (when no rinsing or washing supports flux restoration). When fouling originates from the accumulation of microorganisms and is related to biofilm formation, it is then called biofouling. Fouling can be measured by the **hydraulic resistance** of the fouled membrane with respect to the hydraulic resistance of the clean membrane. **Ultrafiltration** membranes are porous membranes with a pore size range of 2-50 nm driven by pressure. When the pressure to operate the membrane is supplied only by the water head, the driving force is considered to be gravity [70].

Biologically Activated Gravity-Driven Membrane (GDM) technology is based on **stable flux** (daily flux change lower than ±10%) over an extended period with no back-flushing, cross-flow or chemical cleaning required [71]. Such low maintenance is achieved due to the operation at ultra-low pressures enabling the formation of biofilm. The system is considered biologically activated as biofilm consumes contaminants from water when it passes through [61].

Biofilm structure was found to be controlled by metazoans, (multicellular, heterotrophic and eukaryotic organisms, such as nematodes). Their activity reduces membrane **resistance** and enhances flux [72]. As biological treatment for effective carbon removal and limiting bacteria aftergrowth requires a **balance of nutrients**, while handwashing greywater tends to be nutrient-deficient in relation to carbon, nutrient supplementation can be considered [61].

Since this technology was tested for greywater recycling only in locations with moderate to sub-tropical climates, it requires additional investigation before applying under Greenlandic conditions. Research should explore the **effect of temperature**, **activities of Greenlandic metazoan communities** and **nutrient-balancing requirements** as well as the preferable **method of disinfection**.

1.1.3.2 Point-of-Use Disinfection

There are various methods to ensure **microbial water safety** through the removal of pathogens. The most common disinfection processes applied at the Point-of-Use (PoU) are heat treatment, chemical disinfection and ultraviolet (UV) radiation with the following examples:

Heat treatment:

- **Boiling** - raising water temperature to 100°C and maintaining it for at least 1-3 minutes,
- **Pasteurization** - raising water temperature to 60-70°C and maintaining it for a sufficient duration.

Chemical disinfection:

- **Chlorine** - adding chlorine to water, typically in the form of liquid sodium hypochlorite or sodium dichloroisocyanuarate (NaDCC) tablets,
- **Other** - using chlorine dioxide, chloramines, ozone, bromine or silver.

Ultraviolet (UV) radiation:

- **Natural radiation** (solar disinfection, SODIS) - exposing water in clear bottles to direct sunlight (UV-A and UV-B radiation) for a minimum of 6 hours,
- **Artificial radiation** - exposing water to UV-C radiation emitted by low-pressure or medium-pressure mercury lamps or light-emitting diode (LED) lamps.

Each method of disinfection has its own social, economic and environmental impacts that should be assessed in decision-making. Processes have different disinfection efficiencies, often expressed in log removal values (LRV), as well as different technological limitations e.g. on the input water quality. With heat treatment being the most robust in the case of water quality parameters, other methods may be affected by water **turbidity** (chemical disinfection and UV) or even water **pH and temperature** (chemical disinfection). Therefore, water before UV and chemical disinfection should have turbidity below 5 NTU (preferably below 1 NTU) and pH below 8 (disinfection with chlorine) [43].

1.1.4 Perspective on Sustainability

Implementing decentralized handwash greywater recycling in Greenlandic households aligns with the principles of the **Circular Economy**, mainly the elimination of waste and pollution along circulation of materials [73]. It will also contribute to **all dimensions of sustainability**.

By providing access to WASH hardware, such as handwashing stations, and by their recycling abilities to address insufficient water quantities, progress in the WASH sector at the household level (social dimension) will be facilitated. By closing the loop of water intended for hygiene within the household, greywater discharges on the terrain or into the sea will be limited. This will also lower water demand in the location - very beneficial especially in the settlements or towns struggling with water scarcity (environmental dimension). Safe water intended for hygiene contributes to overall better population health contributing to economic growth and lowering resources spent on healthcare (economic dimension) [74].

1.2 Project Objectives and Research Questions

The goal of the project was to explore the **requirements for household greywater treatment technology** to improve hand hygiene in **cold climate conditions** of Greenland, within the context of the current situation in the Arctic WASH sector.

The following research questions were chosen to investigate in the study:

1. **Is water used for personal hygiene in unpiped homes safe?**
   1.1. Does water from household storage contain microbial contamination (HPC, total coliforms)?
   1.2. How is greywater managed after use (discharged, reused without treatment or else)?

2. **Would a Biologically Activated Gravity-Driven Membrane be able to operate in Greenland?**
   2.1. How will lower temperatures affect the performance of the Biologically Activated Gravity-Driven Membrane?
   2.2. Will the Greenlandic metazoan be suitable for pre-seeding the Biologically Activated Gravity-Driven Membrane?
   2.3. What are (if any) the nutrient-balancing requirements for handwash water to ensure better carbon removal for limiting bacterial growth potential?
   2.4. What are the advantages and disadvantages of Biologically Activated Gravity-Driven Membrane in the Greenlandic context?

3. **What would be the best Point-of-Use disinfection technology for unpiped homes?**
   3.1. Which criteria are important to consider in the Greenlandic conditions when selecting technology?
   3.2. What is the importance (weights) of the selection criteria?

2 Materials and Methods

2.1 Project Phases

The project was performed in two phases – fieldwork in Greenland followed by laboratory experiments and literature study on the DTU campus in Lyngby, Denmark.

A week-long fieldwork was conducted in Itilleq, Greenland, in September 2024 to collect data on current household water storage practices in Greenlandic settlements. The study site was chosen based on successful prior research experiences and its accessibility by the seaway from the Arctic DTU campus in Sisimiut. The fieldwork was a combination of qualitative and quantitative research. Water quality analyses were performed in the field laboratory and in the biology laboratory at KTI in Sisimiut. Experiments on greywater recycling with membranes were set up in Denmark in the innovation laboratory and climate room at the Materials and Durability Section of DTU Sustain (Figure 21).

Figure 21. (a) Field laboratory in Itilleq. (b) Microbial analyses in Itilleq. (c) Laboratory work in Sisimiut. (d) Laboratory work in Denmark.

2.2 Water Quality Analyses

2.2.1 Microbiological Parameters

The methods from Maréchal et al., 2023 [63], were adopted to compare with previously achieved results on the microbial quality of water in Greenlandic households.

2.2.1.1 Materials and Equipment

Bacterial content was analyzed using 3M™ Petrifilm™ (supplied by VWR International) Aqua Heterotrophic Count Plates (AQHC) and *E. coli* / Coliforms (EC) for total coliforms and *E. coli*. If samples must have been filtrated, a sterile mixed cellulose ester membrane filter (pore size: 0.45 µm, diameter: 47 mm, Pall Corporation, MI, USA) was placed on the filter base and covered with the funnel, with the suction pump accelerating filtration. Membrane filters were moved with tweezers. The spreader was used to evenly distribute the sample on the plate.

2.2.1.2 Quality Control Measures

Boiled tap water was tested on all types of Petrifilm™ plates as a negative control to rule out cross-contamination during the microbial analyses when used for rinsing between samples. Disinfection wipes were used before microbial testing to sterilize the table surface and between samples. After each day, the funnel, filter base, tweezers and spreader were sterilized by overnight soaking in a 3% chlorine solution.

2.2.1.3 Sample Handling and Preparation

Samples of 1 mL were directly plated onto the Petrifilm™. For larger volumes(25-100 mL), the sample was filtered through the membrane, with 1 mL reserved using a sterile pipette to hydrate the plate after the membrane filter was placed onto the Petrifilm™.

2.2.1.4 Incubation and Reading

Plates were incubated in stacks of 5 to 10. Temperature for EC Petrifilm™ was set to 37°C and plates were read after 24 hours for total coliform count or after 48 hours for *E. coli* count per tested volume. Enumeration of *E. coli* (blue colonies with bubbles) and total coliforms (red and blue colonies with bubbles) followed the manufacturer's instructions (Figure 22). In case the number of bacteria was too numerous to count (TNTC), it was assumed 300 CFU per plate for AQHC and 150 CFU per plate for EC. In some cases of numerous colonies, an estimated count was made by counting colonies in three representative squares and multiplying their average by 20.

During fieldwork, a single transportable, electronic incubator was used for both EC and AQHC Petrifilm™ plates, set to 37°C due to the limited equipment availability and low ambient temperature (<15°C) in the field laboratory. This temperature was chosen because HPC at 37°C is associated with faecal contamination, making it a relevant indicator of health risks despite the lack of guideline values in the Greenlandic Drinking Water Directive. Laboratory experiments, by contrast, incubated AQHC Petrifilm™ plates at 22±2°C for 72 hours to evaluate microbial loads as specified in the Greenlandic Drinking Water Directive.

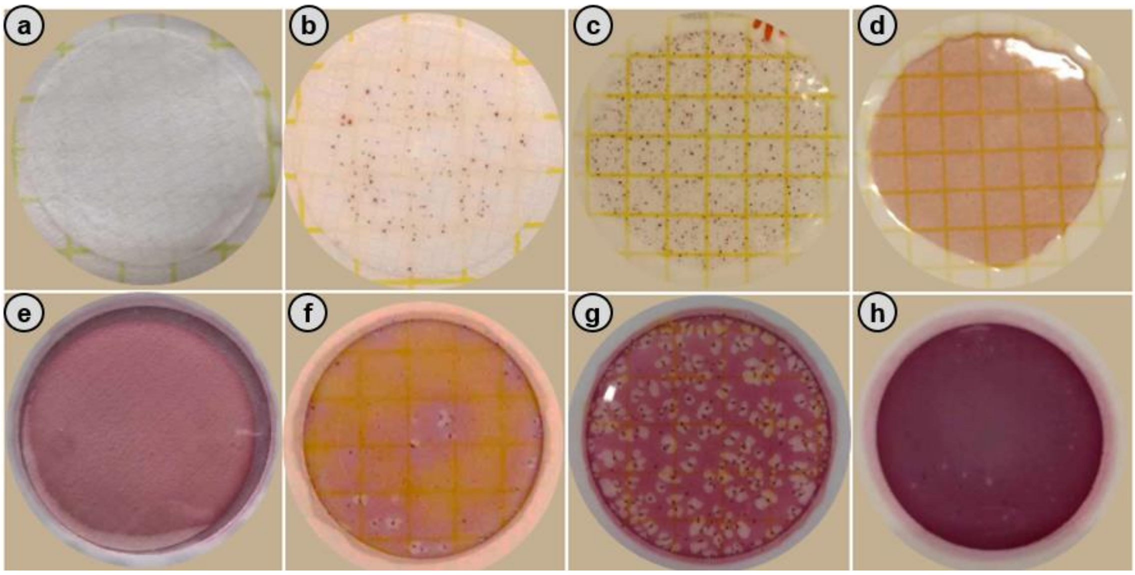


Figure 22. AQHC Petrifilms™: (a) negative test control with filter, (b) plate with filter eligible for counting, (c) directly plated eligible for square-based colony count estimation and (d) directly plated assumed overgrown (300 CFU/1 mL). EC Petrifilms™: (e) negative test control with filter, (f) directly plated eligible for counting, (g) directly plated eligible for square-based colony count estimation of coliforms with air bubbles (h) directly plated assumed overgrown (150 CFU/1 mL).

2.2.1.5 Data Analysis

The results of bacterial counts were log-transformed and shown in the jitter plots prepared using Microsoft Excel version 2016. Jitter plots were used to allow clear visualization by preventing excessive overlapping of data points. Since there are no guidelines for the quality of water intended for handwashing, the results were collated to the guideline values from the Greenlandic Drinking Water Directive

2.3 Physico-Chemical Parameters

Water pH at a temperature in °C was measured using probes - HACH HQd Portable Meter (10/2017, Edition 6) during fieldwork and sensION^{TM} MM374 in the laboratory. Turbidity measurements were done using turbiditimeter - HACH Lange Turbiditmeter 2100P during fieldwork and Xylem Turb 430 IR/T WTW in the laboratory. Before use, the equipment was calibrated with standard solutions provided by the manufacturers. Results are presented in boxplots made in Microsoft Excel version 2016, where the boxes extend vertically from the first quartile (25th percentile) to the third quartile (75th percentile). The mean values are represented by crosses, and the median values are indicated by horizontal lines. The whiskers show the minimum and maximum values, excluding outliers represented by dots. The sample size (N-value) is displayed above each column. Total Organic Carbon (TOC) and elements in water were analyzed by the external laboratory using Multi N/C 3100 from Analytikjena and Inductively Coupled Plasma (ICP) Spectroscopy respectively.

2.4 Fieldwork in Greenland

A site visit was arranged with the municipality office in Itilleq by Arctic DTU. Residents of Itilleq were introduced to the project through posters placed on the announcement boards in two public locations (grocery store and municipal building) at the beginning of the site visit. For more details on posters, outdoor surveys, questionnaires and interviews refer to the thesis “Access and use of water in Greenlandic settlement housing” by Chloe Kiernicki from Tampere University, 2024 [60].

2.4.1 Outdoor Surveys

Two outdoor surveys were organized at the beginning and the end of the site visit. The first one with 16 respondents aimed at gathering preliminary insights about water collection, washbasin use and placement in the households. The second one with 12 respondents was following up on the trends on water storage containers and frustrations around water collection identified during the stay.

2.4.2 Observations and Photographs

Behaviours around water collection and household storage were observed and photographed using a Samsung Galaxy A12 camera (SM-A125F) with anonymization or after permission. The water supply was traced with photographs taken of water intakes, the water treatment plant and taphouses.

2.4.3 Questionnaires and Interviews

Questionnaires and semi-structured interviews focusing on water collection, storage and use were conducted with the help of a local guide through household visits in the different parts of the settlements. 28 out of 45 houses were eligible for a visit and 18 of them were approached with a total of 8 interviews conducted (Figure 23). Each household visit started with the introduction of the visitors and their research, filling in consent forms and questionnaires, followed by a semi-structured interview adapted to the feedback and discussion from residents [60].

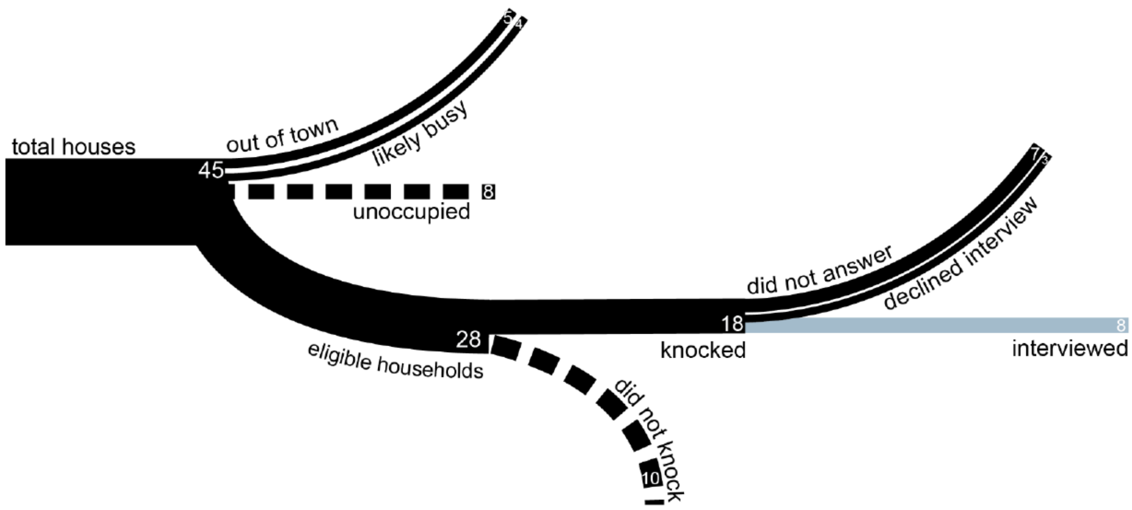


Figure 23. Households interviewed in the settlement [60].

2.4.4 Water Sampling and Testing

Samples (N=68) collected in Itilleq for microbial analysis were taken from all points of the system: the water treatment plant (N=6), taphouses (N=12), cold taps of public service houses and community buildings (N=2), eight households with jerrycans for drinking water (N=24), tanks for two bathroom sinks with one temporary washbasin (N=6), two bathroom washbasins (N=6), and two kitchen washbasins (N=12).

If samples were taken from the sampling point at the water treatment plant or from the tap in the piped building or taphouse, 3 minutes of free water flow was allowed prior to sample collection [75]. Samples were collected in 50 mL sterile test tubes and brought to the field laboratory as soon as possible (no later than 6 hours after collection). Due to the low outdoor temperatures, cooling before analysis was not necessary. To avoid contamination, greywater samples were analyzed last, after all drinking water samples organized according to their sampling time. Greywater (1 mL) was plated directly on both Petrifilms^{TM} while drinking water only on HPC and the rest was filtered for EC. The results were reported back to the community. After microbial testing, pH at temperature and turbidity of samples from distribution (N=36) and for handwashing (N=24) were measured to assess the potential for disinfection.

Additionally, tap water samples from Sisimiut (N=3) and Itilleq (N=3) were collected and transported to Denmark where together with tap water from Lyngby were analyzed for TOC and element contents.

2.4.5 Model for Nutrient-Balancing Requirements

A model developed by Ziemba et al., 2018 [61], was used to investigate in a preliminary manner nutrient-balancing for tap water in Sisimiut, Itilleq and Lyngby based on the nutrient requirements (Table 3). The greywater inputs (Table 4) assumed the use of Palmolive Aquarium soap found in the local store in the settlement (Figure 24). Missing data on water composition in Lyngby were taken from Morsing & Petersen, 2024 [76].

Table 3. Nutrient requirements [61].

Nº	Element	mg/mgC
1.	N	0.24
2.	P	0.06
3.	S	0.02
4.	Ca	0.02
5.	K	0.02
6.	Fe	0.01
7.	Mg	0.01
8.	Mn	0.000042
9.	Cu	0.000067
10.	Zn	0.00016
11.	Mo	0.0000053
12.	Co	0.0000053

Table 4. Handwash greywater inputs [61].

Nº	Input	Value	Unit
1.	Water	1	L
2.	Soap	1.5	mL
3.	Dirt	25.3	mg
4.	Skin	3.2	mg
5.	Moisturizer	8.1	mg

Figure 24. Palmolive Aquarium soap was found in the local store in Itilleq, in September 2024.

2.5 Laboratory Experiments in Denmark

2.5.1 Experimental Setup and Approach

Gravity-driven ultrafiltration membranes were operated in a dead-end mode at a constant transmembrane pressure of 0.60 mH_2O (~59 mbar, ~5,883,990 mPa).

The **experimental setup** (Figure 25) consisted of:

- 1 x plastic bucket of 20 L volume ("recirculation tank"),
- 1 x immersible aquarium pump ("aquarium pump"),
- 1 x plastic bucket of 5 L volume customized with an outflow at the top and two tubing connectors at the bottom ("storage tank"),
- 2 x standard polycarbonate filter holders of 47 mm inner diameter purchased from Whatman ("filtration modules"),
- 2 x new flat sheet polyethersulfone (PES) UF membranes with a nominal cutoff of 100 kDa purchased from Millipore ("UF membrane"),
- 2 x glass bottles for permeate collection.

Connections between different parts of the setup were made with silicone tubing. During operation, feed water was pumped from the recirculation tank to the distribution tank at a rate that ensured constant water level in the distribution tank with excess water leaving the system through overflows.

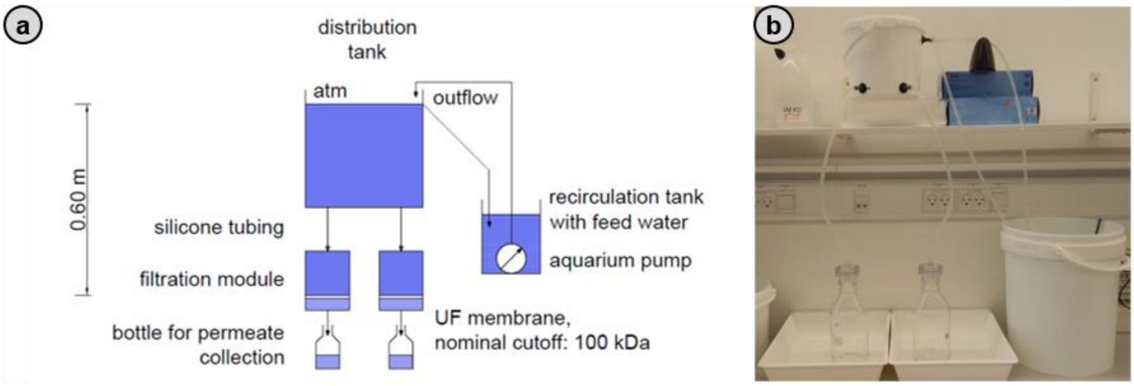


Figure 25. Experimental setup on (a) schematic drawing (made using Autodesk AutoCAD 2024) and (b) in real life.

Eight experimental lines were run on four setups to investigate the effect of temperature and suitability of Greenlandic metazoan for pre-seeding. Experimental lines differed in feed water, temperature conditions or membrane pre-seeding as presented in Figure 26. Due to the shortage of resources, experiments were performed with no duplicates in two series of two setups with new membranes at the time (first greywater at 5°C and 20°C, then greywater at 12.5°C and tap water at 20°C). Each series was running for a period of 21 days. On the 18th day of operation, to investigate the effect of nutrient-balancing, phosphoric acid (H_3PO_4) was added in the amount corresponding to the carbon concentration in the permeate.

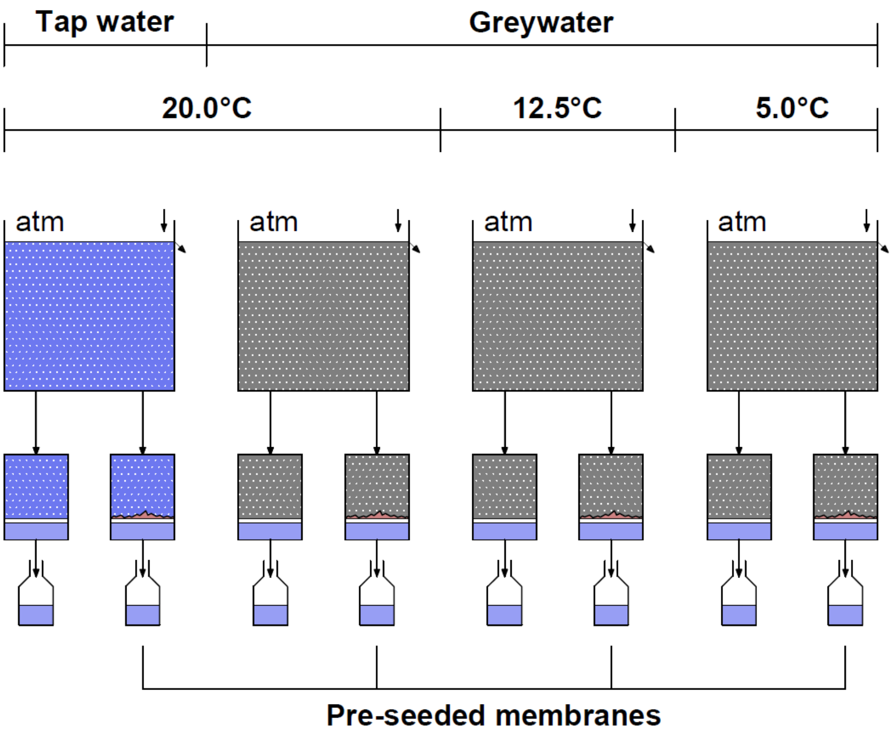


Figure 26. Experimental lines with feed waters, temperatures and membrane pre-seeding conditions (made using Autodesk AutoCAD 2024).

2.5.1.1 Membrane Preparation

New membranes were stored for at least 24 hours in deionized water to remove conservation agents. Water was renewed three times during this washing. Then, membranes were placed in filter holders with the skin side toward solution and deionized water was fed to the setup. The setup operated at the same transmembrane pressure as in later experiments for 24 hours, when permeate volume was measured with a graduated cylinder to determine the clean water flux, which was presented in the box and whiskers plot made in Microsoft Excel version 2016. The Data Analysis Tool in the same software was used to perform an ANOVA test to assess the statistical significance of the difference of mean deionized water flux at different temperatures.

One membrane from each setup was **pre-seeded** with raw water aiming to contain Greenlandic metazoan communities, including nematodes. The presence of nematodes in Greenland was first confirmed in raw waters at water treatment plants in Itilleq and Sisimiut with an optical microscope (Figure 27ab). Then the water for pre-seeding was collected with some sediment at the outlet with backwash water from sand filters in Sisimiut (66.936142°N, 53.629602°W), concentrated to half of its volume and transported to Denmark. To ensure aerobic conditions, outside the duration of air transport, it was kept open at 5°C (Figure 27c). The presence of nematodes in the raw water sample was confirmed under the microscope (Figure 27d) and 5 mL of raw water was added to silicone tubing (Figure 27e) over the filtration module to let it flow on the membrane under the same pressure as experiments were later operating.

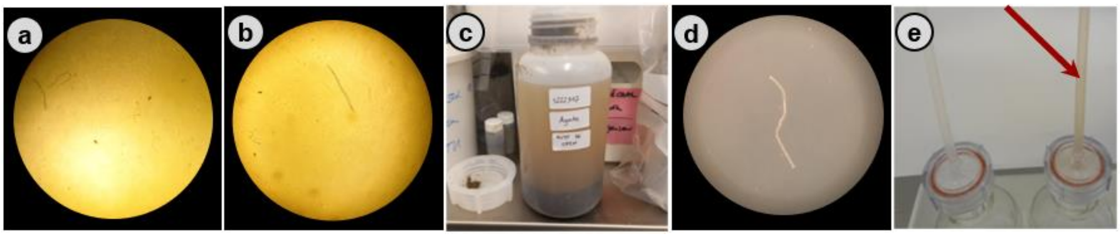


Figure 27. Nematodes in raw water from (a) Sisimiut and (b) Itilleq. (c) Collected sample with (d) nematodes used for (e) pre-seeding membrane by injecting the sample into the silicone tubing marked with red arrow.

2.5.1.2 Feed Water

Greywater for experiments was collected from the bathroom sink (Figure 28) over the course of 1 week prior to each experimental series. To reflect real-life conditions in the household, greywater was stored in the recirculation tank at the same temperature as the experimental setup it was feeding.

The control setup was fed with **tap water** stored in the recirculation tank. Since tap water in Denmark is not chlorinated, it was expected to reflect well conditions in Itilleq.

Figure 28. Greywater collection from the bathroom sink.

2.5.2 Operation of Experiment

Prior to experiments, an **evaporation test** in graduated measuring cylinders was performed and no difference in water loss due to evaporation was recorded over 24 hours for 5°C, 12.5°C and 20°C. Therefore, **permeate flux** was monitored through a daily collection of volumes recorded with graduated measuring cylinders. Cylinder size (1000±10 mL, 500±5 mL, 100±1 mL, 50±1 mL, 25±0.5 mL, 10±0.2 mL or 5±0.1 mL) depended on the collected volume.

Due to the lab scale of experiments, permeate volumes were very small (up to <3 mL), and **microbial testing** was prioritized over physico-chemical parameters. On days 4, 8, 12, 16 and 20 of experiments, permeate was tested for HPC at 22°C (CFU/1 mL), total coliforms and *E. coli* (CFU/1 mL). Only for tap water setup, total coliforms and *E. coli* were counted in 100 mL of filtered water. To assess permeate feasibility for disinfection, after flux stabilization **pH and turbidity** were recorded on the 13th and 14th day of operation respectively. Throughout the whole period of the experiment, collected permeate was also assessed visually. To check the effect of membrane pre-seeding with Greenlandic metazoan communities and the effect of nutrient balancing **TOC** was measured in permeate before and after adding phosphorous (days 17 and 21 of operation). Experimental setups were flushed with deionized water on a weekly basis - feed water was stored and its use continued after cleaning. Filter modules were open and **biofilm growth** was observed and photographed with Samsung Galaxy A12 camera (SM-A125F).

2.5.2.1 Hydraulic Parameters

Permeate Flux

Permeate flux (J) during the experiment was calculated for each experimental line according to Equation 1. The results were presented in the scatter plots with smooth lines and markers prepared in Microsoft Excel version 2016. The difference between results for clean and pre-seeded experimental lines operating at the same temperature were checked with the Wilcoxon Signed-Rank Test performed in RStudio version 2024.09.0+375.

$$J = \frac{\Delta V}{A \cdot \Delta t} \tag{1}$$

Where:

J – permeate flux, L/m^2/h,
ΔV - change in permeate volume, L,
A – filtration area ≈ 0.001735 m^2,
Δt – change in time, h.

Hydraulic Resistance

The hydraulic resistance calculations were made using dynamic water viscosity at a given temperature as presented in Table 5.

Table 5. Dynamic water viscosity at a given temperature [77].

Nº	Temperature	Dynamic water viscosity
	°C	mPa·s
1.	5.0	1.5215
2.	12.5	1.2177
3.	20.0	1.0005

The hydraulic resistance of the clean membrane ($R_{membrane}$) was calculated according to Equation 2 based on the permeate volume recorded with a graduated cylinder in 24 hours of operation with deionized water.

$$R_{membrane} = \frac{TMP}{\eta \cdot J_0} \tag{2}$$

Where:
$R_{membrane}$ – intrinsic hydraulic resistance of the clean membrane, m^{-1},
TMP – transmembrane pressure ≈ 5883990 mPa,
J_0 – permeate flux with the clean membrane, $m^3/m^2/s$,
η – dynamic viscosity of water, mPa·s.

The total filtration resistance of the fouled membrane (R_{total}) was calculated according to Equation 3 based on the permeate volumes daily recorded with a graduated cylinder from experiments operating with the feed water.

$$R_{total} = \frac{TMP}{\eta \cdot J_R} \tag{3}$$

Where:
R_{total} – total filtration hydraulic resistance of the fouled membrane, m^{-1},
TMP – transmembrane pressure ≈ 5883990 mPa,
J_R – permeate flux with the feed water, $m^3/m^2/s$,
η – dynamic viscosity of water, mPa·s.

The hydraulic resistance of the fouling layer ($R_{fouling}$) was calculated according to Equation 4. The results were presented in the scatter plots with smooth lines and markers prepared in Microsoft Excel version 2016.

$$R_{biofilm} = R_{total} - R_{membrane} \tag{4}$$

Where:
$R_{fouling}$ – hydraulic resistance of the fouling layer, m^{-1},
R_{total} – total filtration hydraulic resistance of the fouled membrane, m^{-1},
$R_{membrane}$ – intrinsic hydraulic resistance of the clean membrane, m^{-1}.

2.5.2.2 Removal Efficiency

Efficiencies for removals were calculated based on Equation 5. The results were presented in the column plots prepared in Microsoft Excel version 2016.

$$RE_x = \frac{(x_0 - x)}{x_0} \cdot 100\% \tag{5}$$

Where:
RE_x - removal efficiency of parameter x, %,
x_0 - initial value of parameter x, in its unit,
x - final value of parameter x, in its unit.

2.5.3 SWOT Analysis for Future Study Recommendations

A SWOT analysis was performed to evaluate the potential and challenges associated with greywater recycling using biologically activated gravity-driven membranes in the Greenlandic settlement setting. This approach systematically categorized qualitative and quantitative research outcomes into four dimensions: strengths (S), weaknesses (W), opportunities (O), and threats (T). The analysis distinguished between internal factors (strengths and weaknesses) and external factors (opportunities and threats), allowing to draw conclusions and deliver recommendations for future studies.

2.6 Selection of Disinfection Method

The disinfection method was selected through Multi-Criteria Decision-Making Analysis.

2.6.1 Functional Unit

The functional unit of 18,980 litres of disinfected water intended for handwashing in the household in the Greenlandic settlement over 1 year was chosen based on Equation 6.

$$FU = D_{cap} \cdot cap \cdot T = 20 \frac{L}{person \cdot day} \cdot 2.6\, person \cdot 365\, days = 18{,}980\, L \quad (6)$$

Where:

FU - water volume in the functional unit,
D_{cap} - water demand for basic hygiene = 20 L/person/day [64],
cap - the average number of people living in the household = 2.6 persons (in Itilleq [60]),
T - 1 year period = 365 days.

2.6.2 Selection of Scenarios

One scenario of each disinfection type (heat treatment, chemical disinfection, and UV radiation) was chosen based on its household application in the conditions of Greenlandic settlements. Boiling is already available and does not require any additional equipment. Chlorine tablets have a longer shelf life than chlorine solutions, which makes them more suitable for less frequently supplied locations. They are also safe to handle. With seasonally unavailable solar radiation, UV-C LEDs are a great safe alternative [43].

2.6.3 Assessment Criteria Weights

Assessment criteria were recognized within all dimensions of sustainability, considering their relative importance to disinfecting water intended for personal hygiene. The weights of the criteria were assessed based on the outcomes from the fieldwork through the pairwise comparison. Each criterion was granted 1 point when it was more important than the other, 0.5 points when they were equally important, and 0 points if it was less important than the other. The points for each criterion were summed to deliver the final weight.

2.6.4 Scenario Scoring

Quantitative and qualitative data were obtained through a literature review and digital research. Criteria were marked as beneficial or non-beneficial and evaluated using the scale 1 (high) - 2 (medium) - 3 (low) for non-beneficial and 3 (high) - 2 (medium) - 1 (low) for beneficial criteria based on their numeric values or qualitative assessment.

2.6.5 Decision Matrix

Criteria scores were multiplied by their weights and added up for each scenario. To compare sustainability dimensions across scenarios, the final scores of criteria from the same dimension of sustainability were added up and normalized against the maximum scorable value. Normalized scores within dimensions were plotted in a radar chart made in Microsoft Excel version 2016.

3 Results and Discussion

3.1 Household Water Storage

Detailed findings from outdoor surveys (16 and 12 respondents) and interviews (8 households of 2-6 residents, 3.875 on average) were presented by Kiernicki, 2024 [60]. Only the main points on water sources, gathering, storage and use are listed as a context for results on physico-chemical and microbial water quality parameters.

3.1.1 Water Sources

Evidence of human activity in the area of water springs aligns with responses about collecting **water from nature** (Figure 29). Residents of 3 visited households confirmed that water from natural sources is gathered only for drinking, as a result of indigenous knowledge about its health benefits. All of the households regularly rely on water from **taphouses** as their main water source (Figure 30).

Figure 29. (a) Pipe, (b) hose and (c) pots were encountered in the water springs area in Itilleq (taken by Chloe Kiernicki, September 2024).

Figure 30. Taphouses in Itilleq: (a) taphouse 1 at the groundwater intake, (b) taphouse 2 in the center of the settlement, (c) taphouse 3 at the harbour and (d) taphouse 4 near the school, September 2024.

3.1.2 Water Gathering

Residents gather water **every day** (6 households), **five days a week** (1 household) or **every 2-3 days** (1 household of 2 residents). Water is collected in jerrycans (16 respondents, 8 households) with a typical volume of 10 litres corresponding to its 10 kg weight. Jerrycans are flushed before use and once full, they are carried in hands, on a wheelbarrow (Figure 31), in a repurposed stroller or dragged on a rope in the season (1 interviewee). Due to the mountainous terrain in the settlement, bringing water home is **very challenging**, especially in the extreme climate conditions.

Figure 31. Water collection: (a) rinsing jerrycan, (b) wheelbarrow with jerrycans (c) for uphill transport (pictures taken by Chloe Kiernicki).

Before the introduction of the no-hose policy by Nukissorfiit, residents of households with water tanks were using hoses for water collection. They understand the policy came to life due to the risk of microbial contamination. However, they are also frustrated about being left with no alternatives. Even though one anonymous responder claimed to still use the hose, during the site visit no such action was observed.

3.1.3 Water Storage and Use

Water tanks (Figure 32a) in the houses (2 visited households) are filled with water transferred from jerrycans. Water from the tank is only used for hygiene and cleaning as it's not considered safe enough for drinking due to its longer storage time. 6 visited households do not have a water tank and therefore, **water is stored in jerrycans** usually placed in more than one location, depending on internal household logic (Figure 32bc). The most common places are outside (12 respondents), in the entrance zone named *isaariaq* (4 respondents), or in the kitchen (11 respondents). Storage conditions vary among locations with the **potential of exposure to solar radiation or higher temperatures** in the heated household, enhancing microbial growth in the jerrycans (Figure 32d). This was visually confirmed during the visit, despite rinsing and cleaning practices noted (1 interviewee mentioned using rice as an abrasive agent to remove contamination). In all visited households, water intended for drinking was **poured into pitchers and kept refrigerated**.

Figure 32. Household storage: (a) tank (photo by Chloe Kiernicki), (b) jerrycans stored outside, (c) jerrycans left outside and (d) growth in the jerrycan, September 2024.

Besides drinking, water is primarily used for cooking, washing dishes, handwashing and cleaning. Only one visited household had their own washing machine but still happened to use a service house for laundry. People wash their hands in the **kitchen** (3 visited households), **bathroom** (2 visited households) or in **both spaces** (3 households). Washbasins (Figure 33) are still common **household hardware** (13 out of 16 respondents) available for purchase in the local store. Answers in the free-form responses indicated visible impurities as a driver for changing water after every use or at least every day. However, washbasins with water stored for over 3 days were also encountered during the visit. When houses are unrenovated and there are no pipes for greywater discharges, additional efforts are required to pour greywater on the terrain. Washbasins are also used during community events such as *kaffemik*, a walk-through Greenlandic meetings (15 out of 16 anonymous respondents, 6 out of 8 households).

Figure 33. Examples of washbasins: (a) in the kitchen sink, (b) in the bathroom, (c) temporary stored water in the bathroom sink, September 2024.

Levels of microbial water quality parameters (Figure 34 and Figure 35) varied among sampling points. Bacteria counts of piped water at the water treatment plants, from taphouses and taps in the service and community building were below the detection limit for all parameters - HPC (<1/1 mL), total coliforms and *E. coli* (<1/100 mL). The deterioration of water quality occurred during household storage.

HPCs for drinking water varied among households from absence in one household to $10^{1.5}$ CFU/1 mL in one sample from another, with a median value of $10^{1.1}$ CFU/1 mL in 15 out of 24 samples. **Total coliforms** were present in 14 out of 24 drinking water samples with the plate counts in the range from $10^{0.5}$ to $10^{2.8}$ CFU/100 mL - all exceeding the guideline limit for drinking water. The highest HPCs in water intended for handwashing were found in 12 samples from kitchen basins ($10^{2.5}$-$10^{3.1}$ CFU/1 mL), followed by 6 samples from bathroom basins ($10^{2.5}$ CFU/1 mL) with bacteria absence in 6 samples of water from the tank, even from the temporary “sink basin”. No coliforms were found in the water from the tank, total coliform levels were slightly higher in kitchen and bathroom washbasins with ranges from $10^{4.2}$ to $10^{4.9}$ CFU/100mL and $10^{4.2}$ CFU/100mL respectively - one level of magnitude higher than in the drinking water. No *E. coli* was found in any sample. Since they could have been missed in the case of washbasins with the overgrown Petrifilms™, interpretation of the results was done using counts of total coliforms as limited by the Greenlandic Drinking Water Directive.

In terms of physico-chemical water quality parameters (Figure 36), water samples were on average analyzed for **pH at room temperature** (16.8-17.8°C) with the exception of water samples collected from the water treatment plant and taphouses (average temperature of 12.4°C and 11.8°C respectively). Water pH for almost all samples (59 out of 60) was within the guideline range of 6.5 to 9.5, with an average of 8 (neutral pH) for the distribution system. The biggest ranges of pH were in water from bathroom basins (7.56-8.18), kitchen basins (6.49-7.92) and bathroom sink (7.41-8.68), with the average values of 7.85, 7.17 and 8.06 respectively. As **turbidity** in all samples from the distribution system was below 1 NTU, from the bathroom sink 0.48 NTU for water directly from the tank and 9.99 NTU for water from the temporary washbasin, the maximum value in water intended for handwashing reaches 1,000 NTU in 6 samples equally from bathroom and kitchen washbasins with no samples below 9.99 NTU.

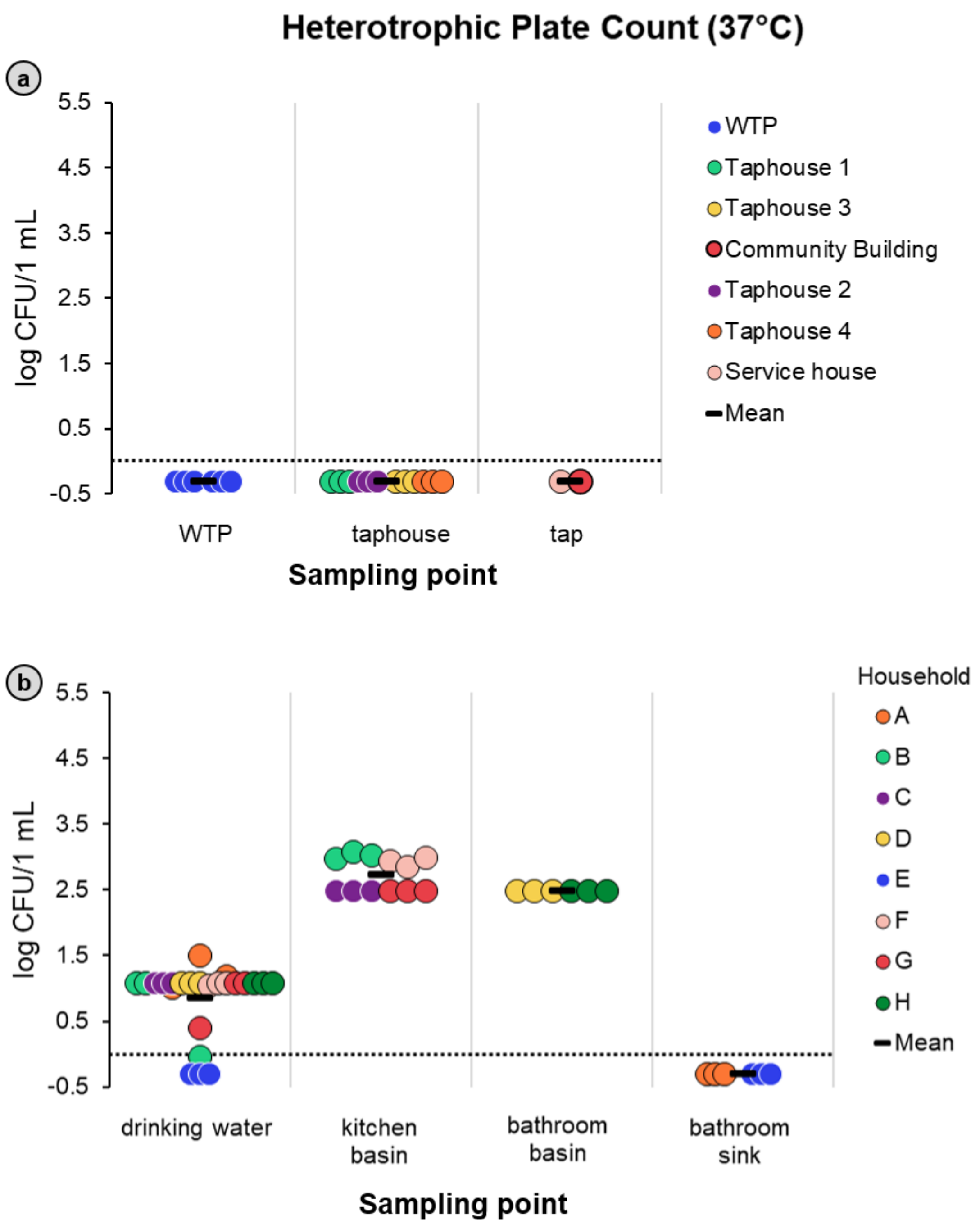


Figure 34. Heterotrophic Plate Count at 37°C in water samples collected from (a) the water distribution system and (b) household storage in Itilleq (data in Table A1, Appendix A). The detection limit was 1 CFU/1 mL (0 log CFU/1 mL), shown as a dotted horizontal line. Non-detects are shown as ½ of the detection limit (-0.301 log CFU/1mL). The short full horizontal line indicates means within each water source.

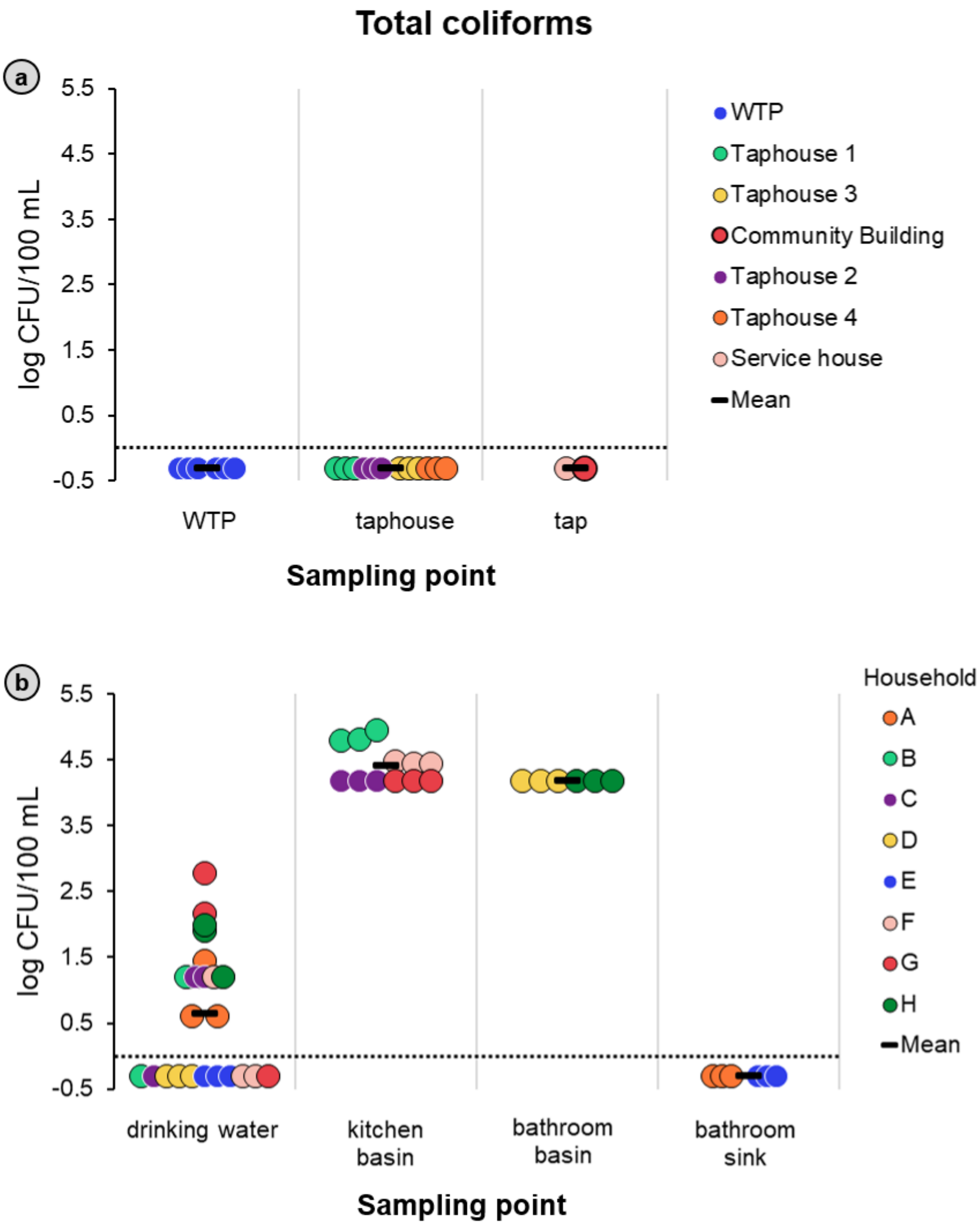


Figure 35. Total coliforms in water samples collected from (a) the water distribution system and (b) household storage in Itilleq (data in Table A1, Appendix A). The detection limit was 1 CFU/100 mL for drinking water and 1 CFU/1 mL for handwash greywater (0 log CFU/1 mL), shown as a dotted horizontal line - this is also a guideline value for drinking water quality. Greywater results were converted from CFU/1 mL to CFU/100 mL to enable one-graph display. Non-detects are shown as ½ of the detection limit (-0.301 log CFU/100 mL). The short full horizontal line indicates means within each water source.

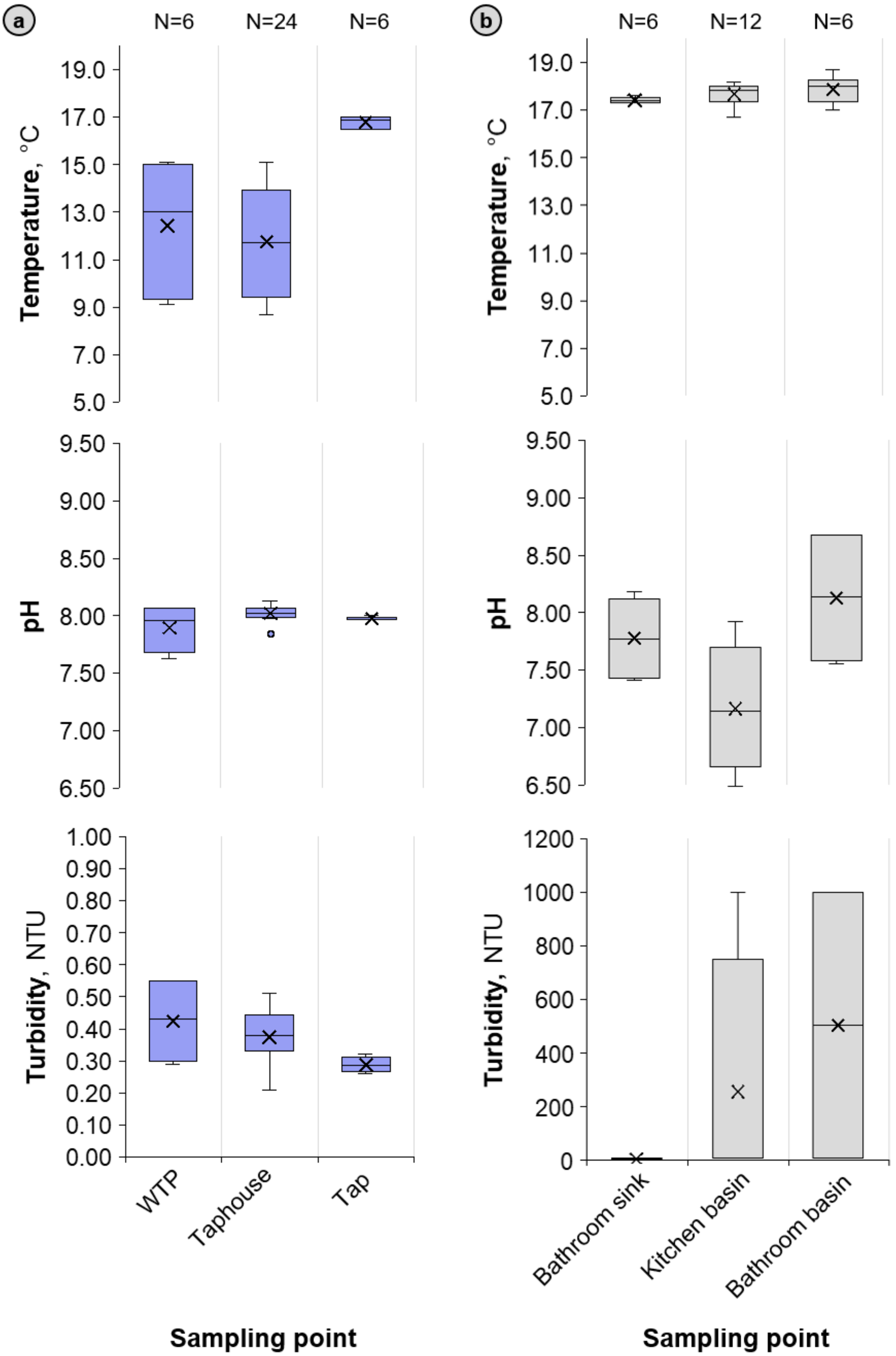


Figure 36. Water pH at temperature in °C and turbidity in NTU from sampling point in (a) the distribution system and (b) from the handwashing hardware with the number of samples (N) in each category shown at the top of the chart (data in Table A2, Appendix A). Note turbidity y-axes.

3.1.4 Key Findings on Household Water Storage

Residents of the settlement gather water from the distribution system, which is microbiologically safe, with levels of HPCs, total coliforms, and *E. coli* below detection limits. The low bacterial counts in piped water align with findings from previous studies. However, in the past, HPCs at taphouses and taps were one to three orders of magnitude higher than at water treatment plants, leading to recommendations for regular use and flushing of taphouses [63]. The observed improvements in bacterial counts suggest these recommendations have been implemented.

Despite frustrations, the “no-hose” policy is followed during water collection. Households with water tanks use the stored water for personal hygiene only, while drinking water is transferred to pitchers and refrigerated. However, **jerrycan storage practices**, including exposure to light and room temperature, may facilitate microbial growth. This was clear in the bacterial analysis, with drinking water from jerrycans showing higher bacterial counts than the distribution system in 21 out of 24 samples for HPCs and in 13 out of 24 samples for total coliforms.

Handwashing practices also contribute to microbial quality deterioration. **Washbasins**, still common in bathrooms and kitchens, present a pathway from WASH-related diseases. Water stored in these basins exhibited significant bacterial loads, with heterotrophic bacteria and total coliform counts reaching up to 1,200 CFU/1 mL and 800 CFU/1 mL respectively. Despite minor differences in water quality, both types of water storage units exposed similar potential for health risks. To ensure microbial safety, water intended for handwashing should undergo **disinfection**. This is feasible for water directly from the distribution system with turbidity <1 NTU and an average pH of 8. However, with turbidity reaching up to 1,000 NTU, direct disinfection of greywater from handwashing is highly limited, requiring prior treatment. In the case of biological treatment, balancing nutrients may increase its efficiency.

Basins, commonly used for hand- and dishwashing, were found available for purchase in the local store remaining the primary option available to residents. Providing **improved handwashing hardware**, e.g. in-home handwashing stations (Figure 37a), as found by Harmon et al., 2024, could stop greywater reuse without treatment in unpiped homes [78]. However, it would not address the challenge of gathering water. Therefore, greywater recycling (Figure 37b) was among the recommendations for handwashing station design for Greenlandic settlements made by Kiernicki, 2024.

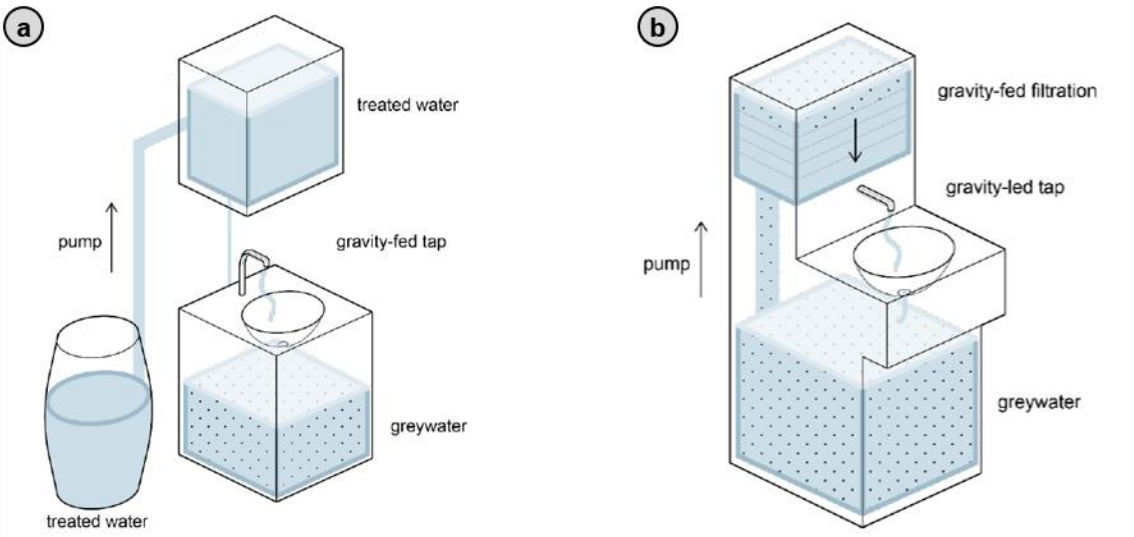


Figure 37. Handwashing stations: (a) without and (b) with greywater recycling [60].

3.1.5 Nutrient-Balancing Requirements

Once the elemental compositions of handwash greywater inputs were found (Table 6), and their individual contributions evaluated (Table 7), final greywater compositions (Table 8) along with their balancing requirements (Table 9) could have been estimated. All **waters exhibited the need of enrichment with nitrogen and phosphorous**, while in Sisimiut water had also low potassium levels.

Table 6. Elemental composition of handwash greywater inputs [61]. Individually collected data are highlighted in red.

Nº	Element	Soap	Dirt	Skin	Moisturizer	Tap water		
						Sisimiut	Itilleq	Lyngby
		mg/L	mg/kg	mg/kg	mg/kg	mg/L	mg/L	mg/L
1.	TOC	24600	437760	761910	112000	2.022	4.435	5.40
2.	N	1780	23470	85714	120	0.262	0.471	0.520
3.	P	51	1090	37140	52	0.007	0.014	0.008
4.	S	5970	3060	6670	160	1.696	2.082	-
5.	Ca	8	28950	47620	10.4	2.466	24.836	90.000
6.	K	92	12860	6670	60	0.374	2.260	4.500
7.	Fe	1	77770	200	1	0.021	0.001	0.013
8.	Mg	8	9620	910	10.4	1.273	1.951	23.000
9.	Mn	0	520	0.6	0.1	0.003	0.003	0.002
10.	Cu	0	180	3.4	0.3	0.008	0.006	0.000
11.	Zn	0	640	110	0.1	0.003	0.004	0.000
12.	Mo	0	4	0.2	0.1	0.009	0.009	-
13.	Co	0	20	0.1	0.1	0.001	0.002	0.000

Table 7. Contribution of individual inputs to handwash water composition.

Nº	Element	Soap	Dirt	Skin	Moisturizer	Tap water		
						Sisimiut	Itilleq	Lyngby
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
1.	TOC	36.9	11.1	2.4	0.9	2.0	4.4	5.4
2.	N	2.7	0.6	0.3	0.0	0.3	0.5	0.5
3.	P	0.1	0.0	0.1	0.0	0.0	0.0	0.0
4.	S	9.0	0.1	0.0	0.0	1.7	2.1	0.0
5.	Ca	0.0	0.7	0.2	0.0	2.5	24.8	90.0
6.	K	0.1	0.3	0.0	0.0	0.4	2.3	4.5
7.	Fe	0.0	2.0	0.0	0.0	0.0	0.0	0.0
8.	Mg	0.0	0.2	0.0	0.0	1.3	2.0	23.0
9.	Mn	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10.	Cu	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11.	Zn	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12.	Mo	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13.	Co	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 8. The final estimated composition of greywater in Sisimiut, Itilleq and Lyngby.

Nº	Element	Handwash greywater		
		Sisimiut	Itilleq	Lyngby
		mg/L	mg/L	mg/L
1.	TOC	53.3	55.8	56.7
2.	N	3.8	4.0	4.1
3.	P	0.2	0.2	0.2
4.	S	10.8	11.1	9.1
5.	Ca	3.4	25.7	90.9
6.	K	0.9	2.7	5.0
7.	Fe	2.0	2.0	2.0
8.	Mg	1.5	2.2	23.3
9.	Mn	0.0	0.0	0.0
10.	Cu	0.0	0.0	0.0
11.	Zn	0.0	0.0	0.0
12.	Mo	0.0	0.0	0.0
13.	Co	0.0	0.0	0.0

Table 9. The balancing requirements for estimated composition of greywater in Sisimiut, Itilleq and Lyngby. Deficient element concentrations are highlighted in red.

Nº	Element	Balancing requirement		
		Sisimiut	Itilleq	Lyngby
		mg/L	mg/L	mg/L
1.	TOC	-	-	-
2.	N	12.8	13.4	13.6
3.	P	3.2	3.3	3.4
4.	S	1.1	1.1	1.1
5.	Ca	1.1	1.1	1.1
6.	K	1.1	1.1	1.1
7.	Fe	0.5	0.6	0.6
8.	Mg	0.5	0.6	0.6
9.	Mn	0.0	0.0	0.0
10.	Cu	0.0	0.0	0.0
11.	Zn	0.0	0.0	0.0
12.	Mo	0.0	0.0	0.0
13.	Co	0.0	0.0	0.0

3.2 Greywater Recycling

3.2.1 Biologically Activated Gravity-Driven Membrane

3.2.1.1 Permeate Flux and Biofilm Formation

The flux through clean membranes operating with deionized water (Figure 38) ranged from 19.9334 to 20.1736 LMH at 5.0°C (N=2), 21.0990 to 21.7384 LMH at 12.5°C (N=2), and 18.1064 to 33.0222 LMH at 20°C (N=4). The average flux values increasing proportionately to temperature align with information from the membrane manufacturer on reduced flow rates in colder conditions [79]. However, **for mean fluxes in different temperatures, no significant difference** (p-value=0.72>0.05) was found in the ANOVA test. The change in the flux of each experimental line was monitored for 18 days when the source of phosphorous was added for the last 3 days of operation (Figure 39). For greywater-fed setups, an immediate flux decline of 83-89% was observed. Flux stabilization (mean flux changes below ±10%) was found on day 5 for 5.0°C at 1.0123 LMH, day 8 for 20.0°C at 1.5862±0.0022 LMH, and day 10 for 12.5°C at 0.4017±0.01433 LMH. On day 14, biofilm developed on the pre-seeded membrane in the greywater-fed setup at 20°C was disturbed (Figure 40) which led to the flux increase. Therefore, only fluxes from days 1 to 13 were included in the Wilcoxon Signed-Rank Test which for other setups was performed on fluxes from days 1 to 18. Only in the setup operating at 12.5°C the difference between clean and pre-seeded membrane was found significant (p=0.03<0.05). However, when only results after flux stabilization were considered, like in other setups, no significant difference was found (Table 10). Until day 6, the greywater-fed setup at 20.0°C had fluxes higher than the setup at 5.0°C which then shifted. The setup at 12.5°C continued with the lowest flux. The dynamic between greywater-fed setups changed after the source of phosphorous was introduced. All setups experienced a flux decline by 29% (greywater-fed clean membrane at 12.5°C) to 69% (greywater-fed setup at 5.0°C). The setup at 20°C performed best, followed by the setup at 12.5°C and with setup at 5°C which performed worst.

Table 10. P-values from Wilcoxon Signed-Rank Test.

Nº	Feed water	Temperature	p-value
1.	Greywater	5.0°C	0.2934
2.	Greywater	12.5°C	0.0294[1] 0.2361[2]
3.	Greywater	20.0°C	0.2439
4.	Tap water	20.0°C	0.2288

[1] *Days 1-18* [2] *Days 10-18*

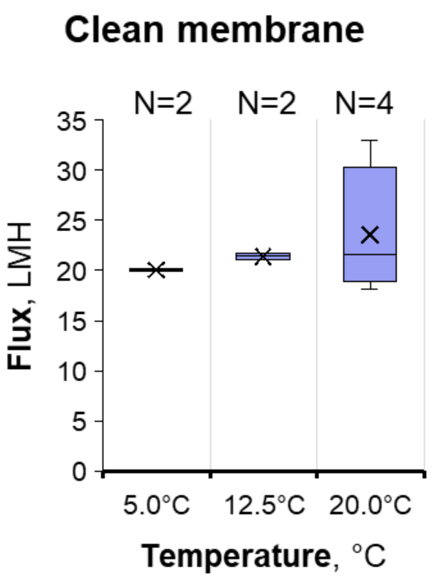


Figure 38. Clean membrane flux with deionized water in LMH over 24 hours in temperatures of 5.0°C, 12.5°C and 20.0°C (data for day 0 in Table B1 & Table B2, Appendix B).

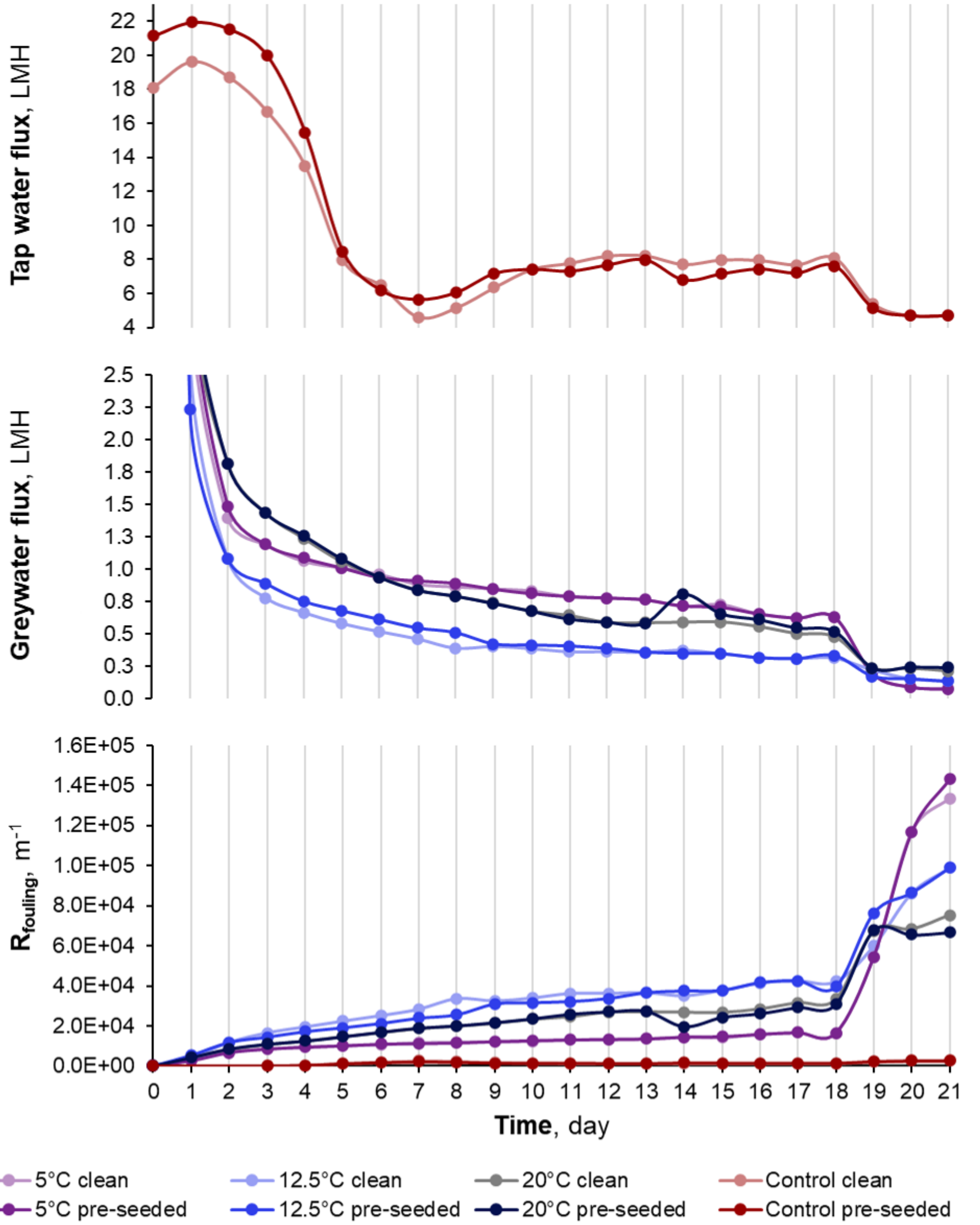


Figure 39. Permeate flux in LMH and hydraulic resistance of the fouling layer in m^{-1} over time for all experimental lines. Note different y-axis for setups fed with greywater and tap water (data in Table B1-Table B4, Appendix B).

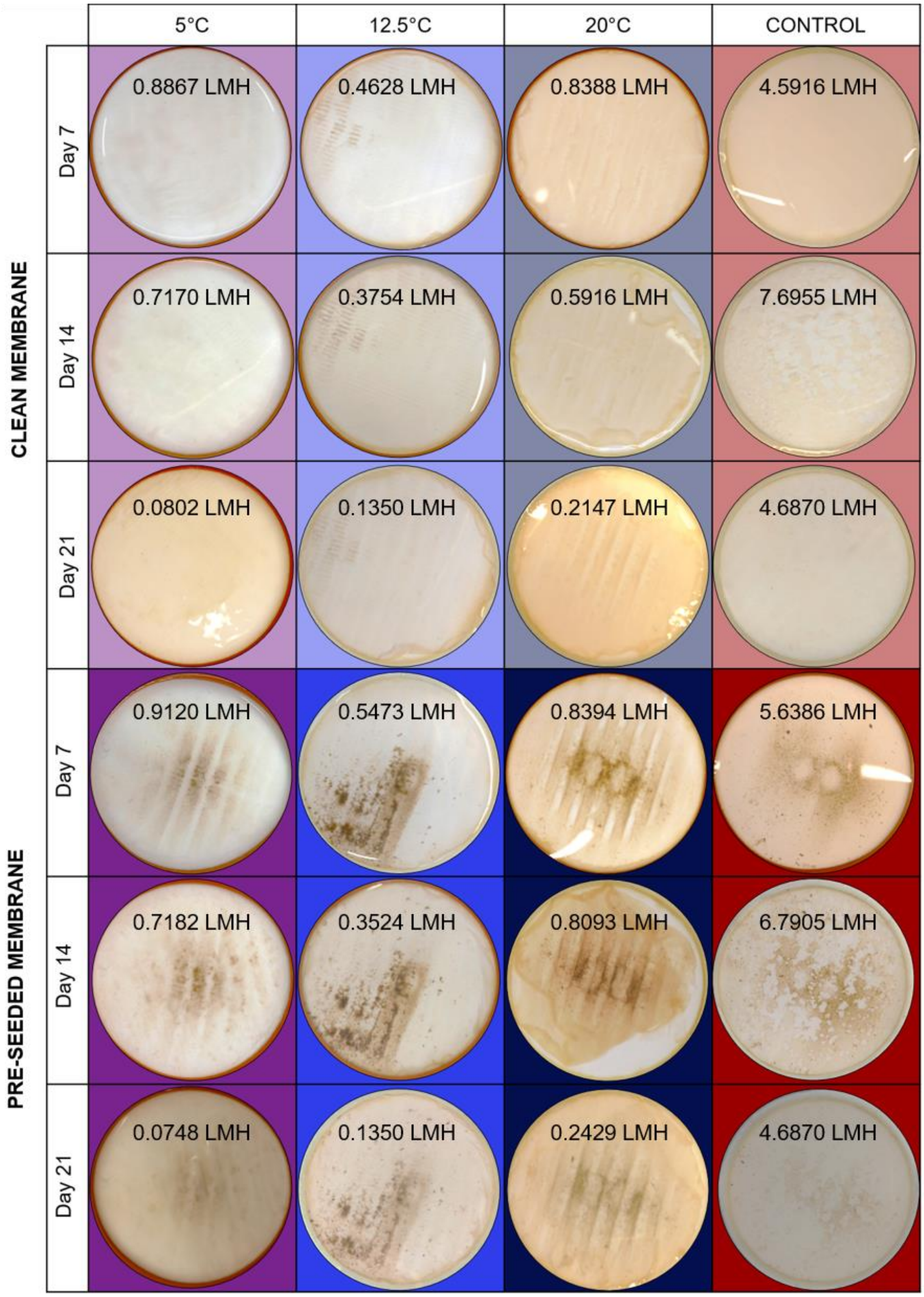


Figure 40. Top pictures of the biofilm developed on the same membranes with the respective flux in LMH for each experimental line on the 7th, 14th and 21st day of operation (data in Table B1 & Table B2, Appendix B).

3.2.1.2 Water Quality Parameters

During operation on days 1-18, **Heterotrophic Plate Counts at 22°C** (Figure 41) in samples from all experimental lines exceeded the plate limit of 300 CFU (overgrown Petrifilms™). Consequently, they did not meet the Greenlandic Drinking Water Directive requirement of <200 CFU/1 mL. Similarly, the guideline value of <1 CFU/100 mL for **total coliforms** (Figure 42) was not met in any greywater samples. However, no coliforms were detected in water samples from the control setup fed with tap water. Total coliform counts in the collected permeate varied across greywater-fed setups. These counts started below the detection limit at the beginning of the experiment (day 4) but reached the overgrown Petrifilms™ threshold (>150 CFU) by day 8 and remained elevated afterwards. The experimental line of 12.5°C showed the most fluctuation in coliform counts. Following the addition of a phosphorous source (days 19-21) corresponding to the TOC content, the nutrient composition in the system has changed. HPC levels decreased in the 12.5°C and control setups, while total coliform counts increased in these setups. When HPCs met the guideline values, total coliforms exceeded.

In terms of physico-chemical water quality parameters (Figure 43), all samples were analyzed for **pH** at the same room temperature of 20.0°C. Greywater had an average pH of 7.61, which was lower than tap water's pH of 8.41. Both, greywater and tap water, had lower pH than their respective permeate with pH on average 10-11% higher for greywater and 4-5% higher for tap water. The difference in pH between clean and pre-seeded membranes was below 0.1% and yet inconclusive. **Turbidity** levels in all greywater samples exceeded the guideline value of 1 NTU, with an average of 25.33 NTU. Tap water also failed to meet the 1 NTU requirement, with an average turbidity of 1.69 NTU, but remained below the maximum permissible limit of 5 NTU for disinfection. Turbidity in the collected permeate varied between 0.03 NTU for a clean membrane fed with tap water to 1.65 NTU for a clean membrane fed with greywater at 12.5°C. Only 2 out of 8 permeate samples exceeded the 1 NTU limit, and all remained below 5 NTU. Permeate, assessed visually throughout the experiment, appeared clear and appealing compared to the cloudy greywater. **Turbidity removal rates** were consistently high across all samples, ranging from 93.49% for pre-seeded control to 98.33% for greywater-fed clean membrane at 20°C (Figure 44). Higher turbidity removal rates were found for clean membranes in the control and greywater-fed setups at 5.0°C and 20°C. Greywater-fed setup at 12.5°C had a higher turbidity removal rate for pre-seeded membrane.

The concentrations of **total organic carbon** in both, raw and phosphorous-enriched greywater were found unreliable - TOC level over 900 mgC/L was 6 to 20 times higher than values from literature for handwash greywater [61]. Therefore, TOC removal rates were not calculated and only the TOC concentrations in permeate during normal operation and after phosphorous enrichment are presented (Figure 45) with levels remaining higher than the literature findings. However, since collected permeate volumes were too small to allow replicates and TOC analyses of tap water in Lyngby had a coefficient of variation of 43% (compared to tap water analyses in Sisimiut with 13% and Itilleq 4%), their reliability remains unsure and further analyses are suggested. The concentration of TOC for all greywater-fed experimental lines decreased after enrichment with phosphorous with the highest rates at 20°C and lowest at 12.5°C. For all these setups the decrease rate was higher for clean membranes (70% vs. 19% at 5°C, 13% vs. 3% at 12.5°C, and 92% vs. 31% at 20°C). In the pre-seeded control setup, TOC concentration significantly increased (from 1.3 to 15.9 mg/L) which was found too unusual to explain. Results for TOC were tested for correlation with turbidity levels and the correlation coefficient was found as 0.5078 which indicates moderate positive correlation (TOC increases as turbidity increases) with other variables potentially affecting one of the parameters.

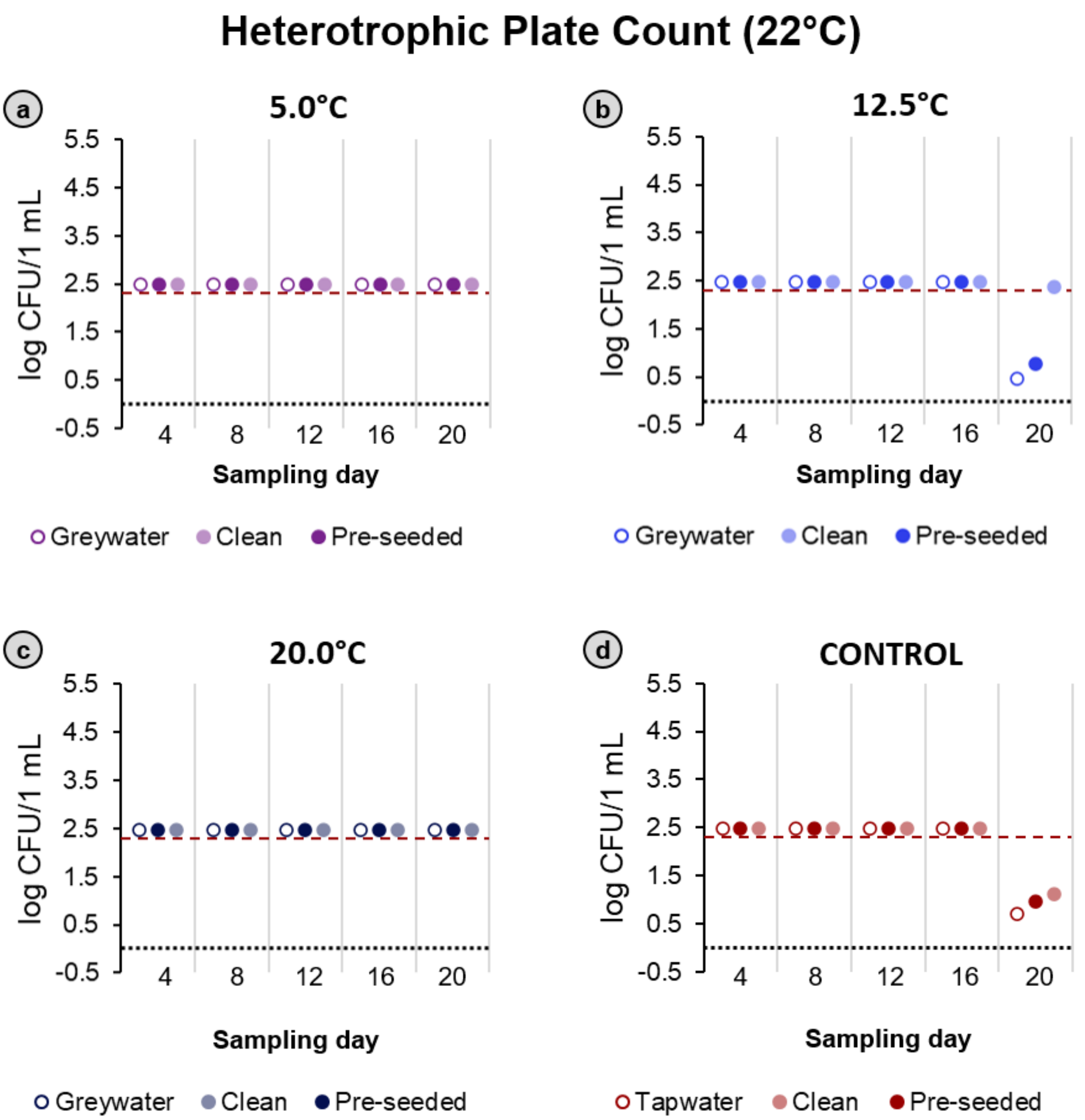


Figure 41. Heterotrophic Plate Counts at 22°C in feed water and permeate samples collected from setups with greywater at (a) 5°C, (b) 12.5°C, (c) 20.0°C and (d) from control with tap water (data in Table B5, Appendix B). The detection limit was 1 CFU/1 mL, shown as a dotted horizontal line. The guideline value of 200 CFU/1 mL (2.3 log CFU/1 mL) is shown as a red dashed line. Non-detects are shown as ½ of the detection limit (-0.301 log CFU/1 mL).

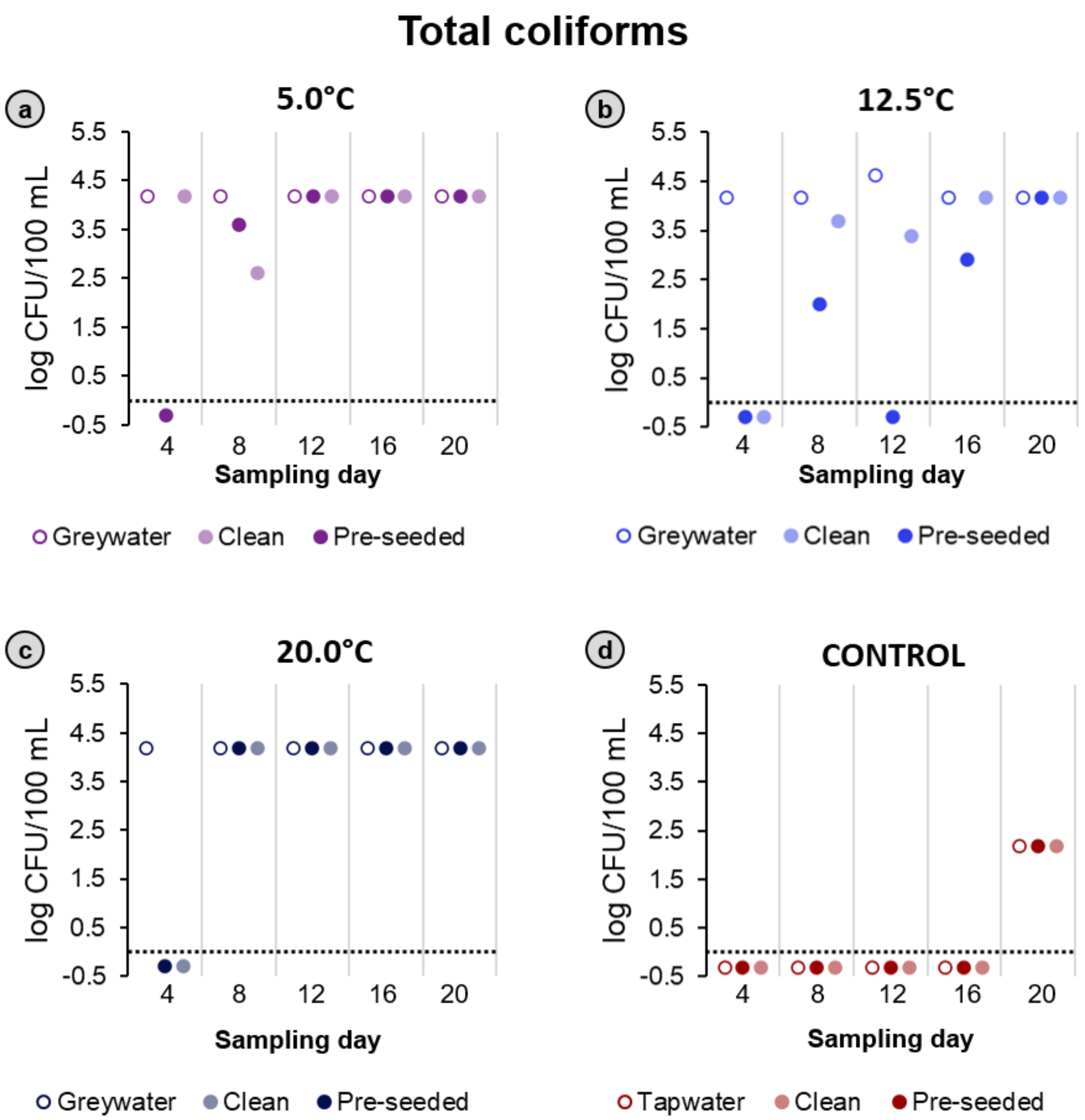


Figure 42. Total coliforms in feed water and permeate samples collected from setups with greywater at (a) 5°C, (b) 12.5°C, (c) 20.0°C and (d) from control with tap water (data in Table B6, Appendix B). The detection limit was 1 CFU/1 mL for setups fed with greywater and 1 CFU/100 mL for the setup fed with tap water, shown as a dotted horizontal line - this is also a guideline value for drinking water quality. Results from setups with greywater were converted from CFU/1 mL to CFU/100 mL to enable graph comparison. Non-detects are shown as ½ of the detection limit (-0.301 log CFU/100mL).

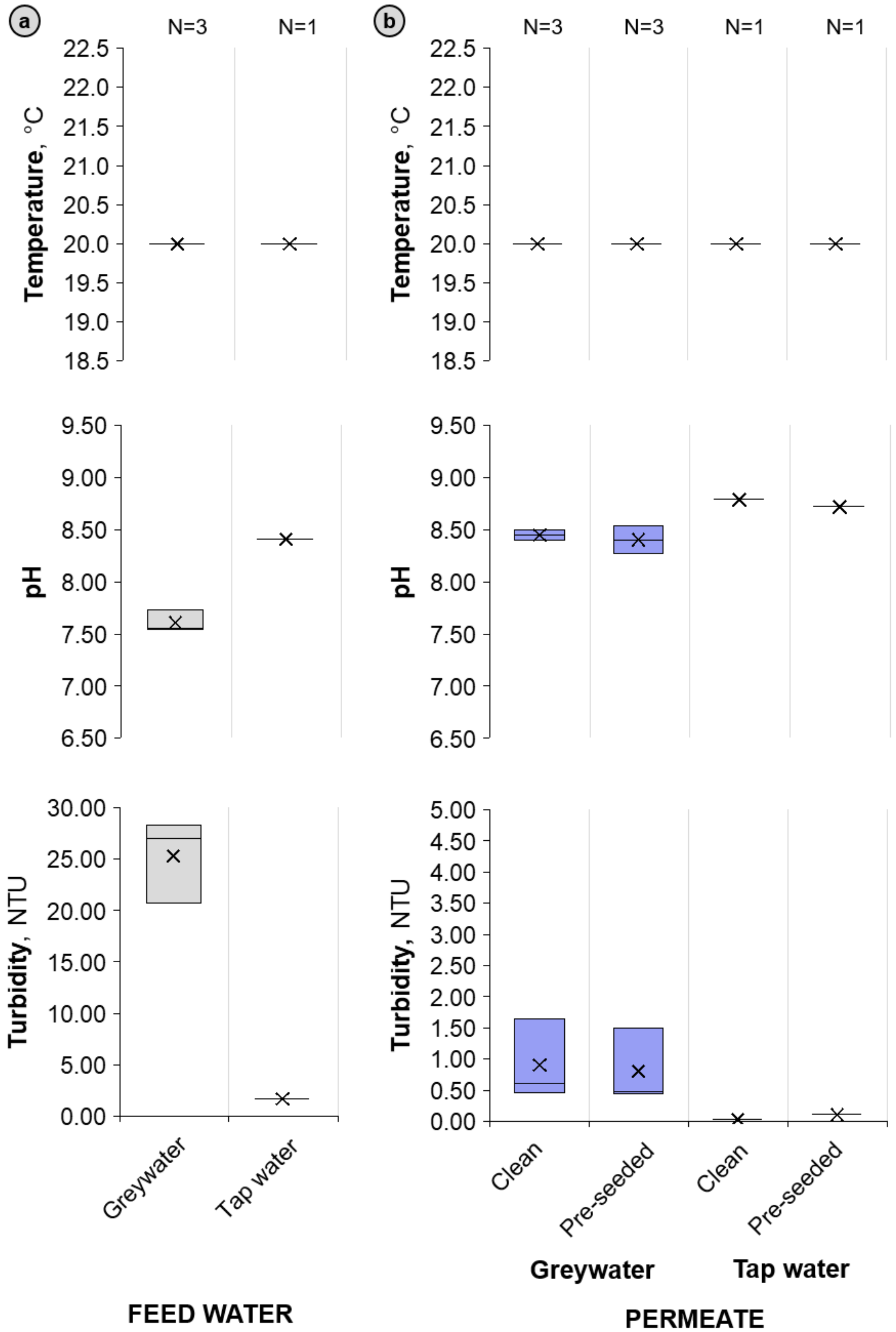


Figure 43. Water pH at temperature in °C and turbidity in NTU of (a) feed water and (b) permeate with the number of average measurement values (N) in each category shown at the top of the chart (data in Table B7, Appendix B). Note turbidity y-axes.

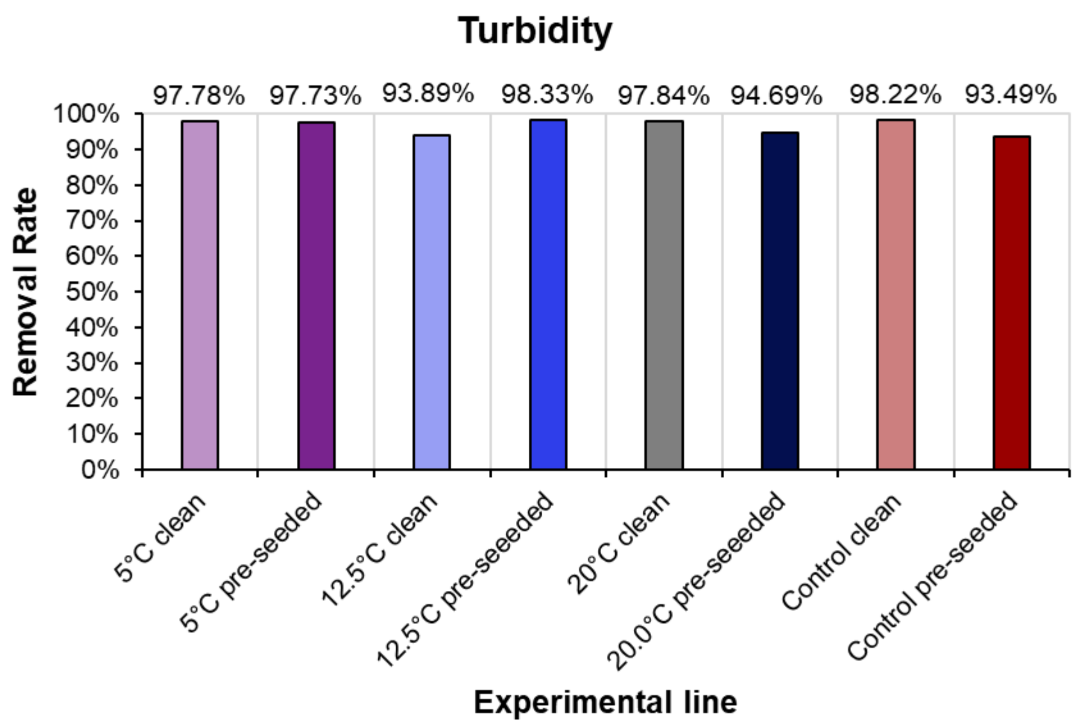


Figure 44. Turbidity removal rates in % for each experimental line (data in Table B7, Appendix B).

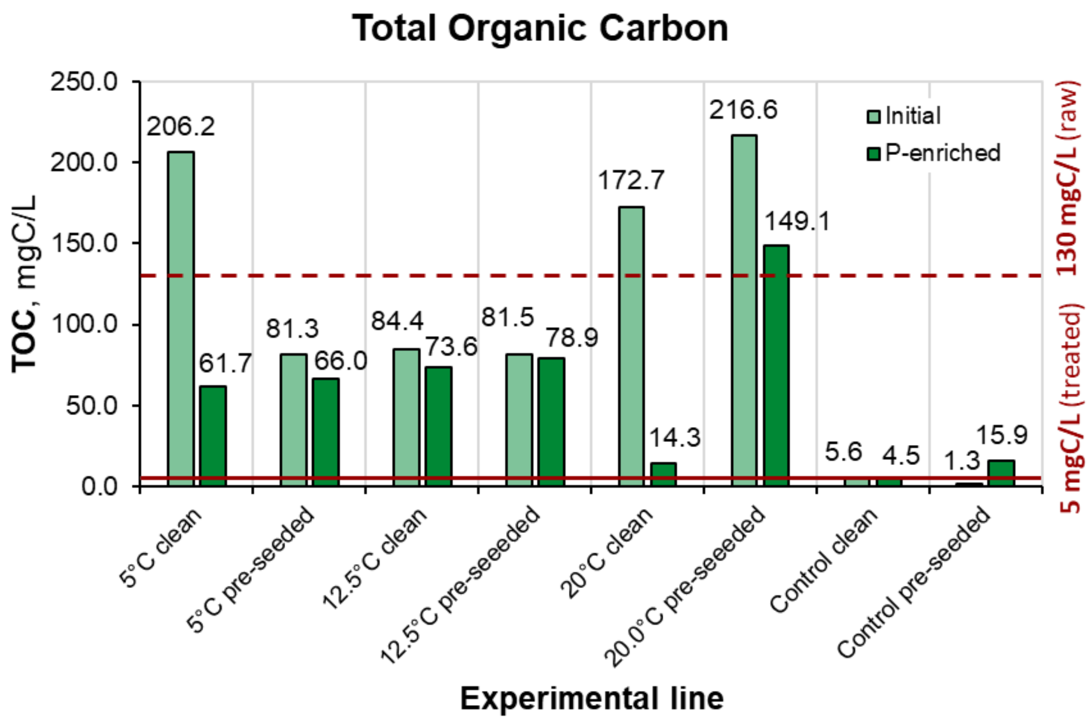


Figure 45. Total organic carbon in mgC/L for each experimental line before and after enrichment with phosphorous (data in Table B8, Appendix B). The red dashed horizontal line indicates the raw handwash greywater level from Ziemba et al., 2018 [61], and the red full horizontal line indicates the treated handwash greywater level from Reynaert et al., 2020 [69].

3.2.1.3 Key Findings on GDM

Even though in general flux increases with temperature, the difference for clean water filtration was found insignificant. For greywater-fed systems in phosphorous-deficient conditions, the lowest flux was obtained at a temperature of 12.5°C which compared to 5.0°C or 20.0°C seems to be preferable for microbial growth. After phosphorous enrichment, the hydraulic resistance of the fouling layer increases, probably due to the biofilm growth, with the highest rate for 5.0°C and the lowest for 20.0°C resulting in the flux increasing with temperature as expected.

Due to the microbial content exceeding guideline values, permeate from all experimental lines at every stage of the experiment **must have been disinfected** before use. Turbidity below 1 NTU (6 out of 8 experimental lines) and below 5 NTU (8 out of 8 experimental lines) made permeate **suitable for turbidity-sensitive** disinfection methods such as UV radiation or chlorination. However, if chlorination was chosen, **pH>8 may affect its efficiency** for all experimental lines.

Enrichment with phosphorous, a nutrient that the feed waters were deficient with, resulted in lower **TOC** levels in the permeate - the lower, the higher the temperature. Clean membranes were found to perform better than pre-seeded membranes which together with the unusual increase in TOC in the pre-seeded control setup support a lack of confidence about the results. Therefore, the results are found inconclusive and further investigation on the effects of nutrient-balancing as well as its effect on biofouling and flux decline should be investigated with ongoing measurements. TOC is an important parameter when designing the disinfection process as its high concentration may lead to the creation of disinfection-by-products (DBP). However, these are a bigger concern for drinking water and thus limited in various guidelines. In the case of handwashing, the risk through skin contact exposure is relatively low, yet should not be neglected.

3.2.1.4 SWOT Analysis and Future Study Recommendations

Biologically activated gravity-driven membrane was found suitable to treat greywater from handwashing in various temperatures. No energy was used for filtration itself and therefore its operation cost is considered low. Due to the high turbidity removal, treated water was suitable for different methods of disinfection as a next step. The system is relatively simple to operate and may have a long life (up to 10 years for clean water), if well maintained with almost no residual waste in the period [80]. However, it was yet not tested with kitchen greywater. During fieldwork, a joint use of WASH hardware for both, handwashing and washing dishes, was found common and worth addressing. Feeding the setup with kitchen greywater, as an example of improper handling, may lead to membrane clogging with oil or other residuals. Despite technology development and the attempts for cheaper production, prices of membranes remain high (350-1,400 DKK/m^2) with practically no perspectives for local production [80]. Membranes also have a limited flow rate and scalability - 1 m^2 of membrane area with the assumed flux of 1 LMH would be able to treat 24 L of water daily. To save on space, the membrane can be arranged in the standing sandwich membrane module, but the high price of more m^2 will remain. This technology requires user education but also maintenance every 6-12 months performed by qualified employees. This may create job opportunities in the membrane service. However, the need for external help and the dependence on the supply chain may jeopardize the use of technology in remote locations. The analysis of strengths, weaknesses, opportunities and threats is presented in Figure 46.

	beneficial	non-beneficial
internal	**STRENGTH**	**WEAKNESSES**
	Application for handwash greywater	No proven application for kitchen greywater
	Energy efficiency (low operation cost)	High membrane price
	High turbidity removal (enabled disinfection)	No local production
	Relatively simple to operate	Limited flow rate and scalability
	Long life if well maintained (~10 yrs for clean water)	Sensitive to improper handling
external	**OPPORTUNITIES**	**THREATS**
	Educational programmes for users	Risk of mismanagement
	New job opportunities in membrane service	Lack of qualified service (every 6-12 months)
	Technology development (cheaper production)	Dependence on the supply chain

Figure 46. SWOT analysis for biologically activated gravity-driven membrane technology (made in Miro).

It is recommended to further explore other technologies suitable for greywater recycling in the Greenlandic settlement housing. Also the ones with reasonably higher energy demand. Studies should focus on:

1) **Robustness**, also in handling greywater from different household sources,
2) **Locally produced materials**, potentially reducing the initial cost,
3) **Limited waste production,** as waste management remains a challenge,
4) **System scalability and design optimization**, as households differ in size.

3.2.2 Point-of-Use Disinfection

3.2.2.1 Assessment Criteria

Disinfection scenario criteria of assessment were selected within social, economic and environmental & technological dimensions of sustainability as presented in Table 11, Table 12 and Table 13.

Table 11. Social criteria.

Nº	Society
1.	Health impacts
1a	Water safety (pathogens removal, residuals)
1b	Recontamination risk
1c	Safety of use
2.	Cultural acceptance
3.	Access to equipment and supply
4.	Required education
5.	User effort
5a	Time effort
5b	Physical effort

Table 12. Economic criteria.

Nº	Economy
1.	Initial purchase
2.	Operation & maintenance (O&M)
2a	O&M cost
2b	Supply chain dependence

Table 13. Environmental & technological criteria.

Nº	Environment & Technology
1.	Input water quality
2.	Residual waste
3.	Durability and lifespan

3.2.2.2 Criteria Weights

The results of the pairwise comparison of assessment criteria are presented in Table 14.

The most important are:

- Water safety (weight 10.5),
- Cultural acceptance (weight 9.5),
- Initial cost (weight 9.5),
- Access to equipment and supplies (weight 9),
- Operation & maintenance cost (weight 8.5),
- Safety of use (weight 8).

The least important are:

- Recontamination risk (weight 2),
- Time effort (weight 3.5),
- Waste (weight 4),
- Durability and lifespan (weight 4),
- Physical effort (weight 5),
- Required education (weight 5).

Table 14. Pairwise comparison of criteria. Criteria with the five highest weights are bolded.

Nº	Criterion	Water safety	Recontamination risk	Safety of use	Cultural acceptance	Access	Required education	Time effort	Physical effort	Initial cost	O&M cost	Supply chain dependence	Input water quality	Residual waste	Durability and lifespan	**Weight**
1.	**Water safety**		1	0.5	0.5	1	1	1	1	0.5	0.5	1	0.5	1	1	**10.5**
2.	Recontamination risk	0		0	0	0	0	0.5	0	0	0	0	0.5	0.5	0.5	2
3.	**Safety of use**	0.5	1		0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	0.5	0.5	1	**8**
4.	**Cultural acceptance**	0.5	1	0.5		0.5	0.5	1	1	0.5	0.5	1	0.5	1	1	**9.5**
5.	**Access**	0	1	0.5	0.5		0.5	1	1	0.5	1	0.5	0.5	1	1	**9**
6.	Required education	0	1	0.5	0.5	0.5		0.5	0.5	0	0	0	0.5	0.5	0.5	5
7.	Time effort	0	0.5	0.5	0	0	0.5		0.5	0	0.5	0.5	0	0	0.5	3.5
8.	Physical effort	0	1	0.5	0	0	0.5	0.5		0.5	0.5	0.5	0	0.5	0.5	5
9.	**Initial cost**	0.5	1	0.5	0.5	0.5	1	1	0.5		0.5	1	1	1	0.5	**9.5**
10.	**O&M cost**	0.5	1	0.5	0.5	0	1	0.5	0.5	0.5		0.5	1	1	1	**8.5**
11.	Supply chain dependence	1	1	0	0	0.5	1	0.5	0.5	0	0.5		1	0.5	0.5	7
12.	Input water quality	0.5	0.5	0.5	0.5	0.5	0.5	1	1	0	0	0		0.5	1	6.5
13.	Waste	0	0.5	0.5	0	0	0.5	1	0.5	0	0	0.5	0.5		0	4
14.	Durability and lifespan	0	0.5	0	0	0	0.5	0.5	0.5	0.5	0	0.5	0	1		4

3.2.2.3 Scenario Scoring

In addition to the functional unit of 18,980 L of water per household over 1 year, to assign values to assessment criteria for boiling, NaDCC chlorine tablets and UV-C LED disinfection scenarios (Figure 47), the following assumptions were made:

1) Jerrycans and electric kettles are already at the households,
2) Price for energy is 1.87 DKK/kWh [36].

Figure 47. Disinfection scenarios: (a) boiling (from Pisiffik website [81]), (b) chlorine tablets (from the Sisimiut Outdoor website [82]), and (c) UV-C LEDs (from the producer's catalogue, Appendix D).

Detailed calculations for a scenario review can be found in Appendix E.

Scenario Review

a) Boiling

Water boiling is a **known and well-accepted** method of disinfection that **does not require much training** to perform [43]. The electric kettle used for boiling is already in the household with an assumed lifespan of 4.4 years [83], and therefore, in the considered period of 1 year, **no additional purchases** are planned. Operation requires **minimum physical effort** to pour water into and from the kettle. Additionally, regular cleaning of scale deposits with vinegar or citric acids may be required. Boiling is **safe to use**, with the only risks related to skin contact with very hot water posing a danger of burn, especially for children. It is **efficient** at pathogen removal (6-9+ LRV [43]) and can be applied despite the **poorer quality of input water**. However, it does not prevent **water recontamination** during storage [43]. Boiling **takes time,** approximately 791 hours per year (disregarding cooling time) and **requires electricity** (approximately 2,182.7 kWh during the year, corresponding to a total cost of 4,082 DKK).

b) NaDCC chlorine tablets

Chlorine tablets Katadyn Micropur Forte MF1 (Appendix C) are **available for purchase** in the store “Sisimiut Outdoor” in Sisimiut for a price of 220 DKK per package [82] corresponding to the yearly cost of 41,756 DKK. They have a **shelf life of 2-3 years** and, therefore can be safely stored at home in a way preventing the **risk of ingestion** by children. The use of chlorine requires **no additional equipment** but the already-owned jerrycans. On the other hand, it requires input water turbidity <5 NTU, pH <8 and temperature >20°C. In these conditions, it should effectively **inactivate pathogens** (1-2+ LRV [84]) in 30 (bacteria and viruses) to 120 minutes (amoebas and giardia). When the concentration of chlorine is sufficient, it also provides **residual protection** from microbial contamination (up to 6 months due to the silver content in tablets). However, high doses may also contribute to skin irritation [85]. Using chlorine does not require any special training. The chlorine tablet must be placed in the container, after 10 minutes water should be mixed and the rest of the disinfection time should be waited. In Greenlandic settlements, **raising awareness** about chlorine may be necessary, as people are not used to chlorinated water, expressing either distrust or dislike for it when encountered in water intended for drinking [63] - however, it may not be relevant for handwashing. Packaging of chlorine tablets must be disposed of after use and therefore it contributes to 17 g of **residual waste**, 3,226.6 g per year.

c) UV-C LED

PearlAqua Micro 3B from Aquisense Technologies (Appendix D) is a UV-C LED-based method of disinfection for domestic use that without much effort from the user in seconds **removes over 99.99%** (4+ LRV) of pathogens from water, including cryptosporidium and giardia. Likewise boiling, this solution does not protect water from **recontamination**. Even though UV treatment is already **widely used** in Greenland at the water treatment plants, and therefore, culturally accepted, household application would require **safety training** (with a focus on avoiding exposure to UV radiation). To operate, UV-C LEDs require a relatively small **energy supply** (4.1 kWh per year) with a cost equivalent of 7.7 DKK. Since UV-C LEDs were not yet found for sale in Greenland, shipping from the UK was considered. The price of the UV equals 1548 DKK [86] with an additional 140 DKK for shipment [87] (currency rate exchange for 17/01/2025) giving a total of 1,688 DKK initial cost. Input water must have turbidity <5 NTU and transmittance >70% (at 254 nm over 1 cm path length). There is a need for yearly inspections, which may contribute to the creation of **new workplaces** but would also require more advanced training. With a **lifespan of 7.9 years**, 77 g (9.7 g per year) UV-C LEDs must be properly disposed of. However, due to the lack of mercury, they do not have to be treated as toxic waste.

Criteria Evaluation

Values or scores for criteria evaluation based on their contribution to each scenario are presented in Table 15 and Table 16.

Table 15. Values with units (1, 7, 9, 10, 13 & 14) or scores in 3-2-1/1-2-3 scale (2-6, 8, 11 & 12) for criteria evaluation. Beneficial criteria (1, 3-5 & 14) are marked with green. Non-beneficial criteria (2, 6-13) are marked with red.

Nº	Criterion	Scenario		
		Boiling	Chlorine tablets	UV-C LEDs
1.	Water safety	99.9999%	99%	99.99%
2.	Recontamination risk	1	3	1
3.	Safety of use	3	1	2
4.	Cultural acceptance	3	1	3
5.	Access to equipment	3	2	1
6.	Required education	3	1	2
7.	Time effort	2.5 min	120 min	1 min
8.	Physical effort	2	2	3
9.	Initial cost	0 DKK	0 DKK	1,688 DKK
10.	O&M cost	4,082 DKK	41,756 DKK	7.7 DKK
11.	Dependence on the supply chain	3	1	2
12.	Input water quality	3	2	2
13.	Waste	0 g	3,226.6 g	9.7 g
14.	Durability and lifespan	4.4 years	3 years	7.9 years

Table 16. Criteria evaluation based on their contribution to each scenario on 3-2-1 scale.

Nº	Criterion	Scenario		
		Boiling	Chlorine tablets	UV-C LEDs
1.	Water safety	3	1	2
2.	Recontamination risk	1	3	1
3.	Safety of use	3	1	2
4.	Cultural acceptance	3	1	3
5.	Access to equipment	3	2	1
6.	Required education	3	1	2
7.	Time effort	2	1	3
8.	Physical effort	2	2	3
9.	Initial cost	3	3	1
10.	O&M cost	2	1	3
11.	Dependence on the supply chain	3	1	2
12.	Input water quality	3	2	2
13.	Waste	3	1	2
14.	Durability and lifespan	2	1	3

3.2.2.4 Decision Matrix

Criteria scores were multiplied by their weights (Table 17). **Boiling** was found to be the best disinfection scenario (final score 251.0), second best were **UV-C LEDs** (194.0) and **chlorine tablets** were closing the ranking (135.5). Normalized results for scenario score within each dimension of sustainability are presented in Figure 48 confirming economy as the weakest point of the UV LED disinfection - mainly due to its high initial cost (1,688 DKK).

Table 17. The decision matrix with final scores for each disinfection scenario in bold. The highest score is marked in red.

Nº	Criterion	Scenario		
		Boiling	Chlorine tablets	UV-C LEDs
1.	Water safety	31.5	10.5	21.0
2.	Recontamination risk	2.0	6.0	2.0
3.	Safety of use	24.0	8.0	16.0
4.	Cultural acceptance	28.5	9.5	28.5
5.	Access to equipment	27.0	18.0	9.0
6.	Required education	15.0	5.0	10.0
7.	Time effort	7.0	3.5	10.5
8.	Physical effort	10.0	10.0	15.0
9.	Initial cost	28.5	28.5	9.5
10.	O&M cost	17.0	8.5	25.5
11.	Dependence on the supply chain	21.0	7.0	14.0
12.	Input water quality	19.5	13.0	13.0
13.	Waste	12.0	4.0	8.0
14.	Durability and lifespan	8.0	4.0	12.0
15.	**SUM**	**251.0**	**135.5**	**194.0**

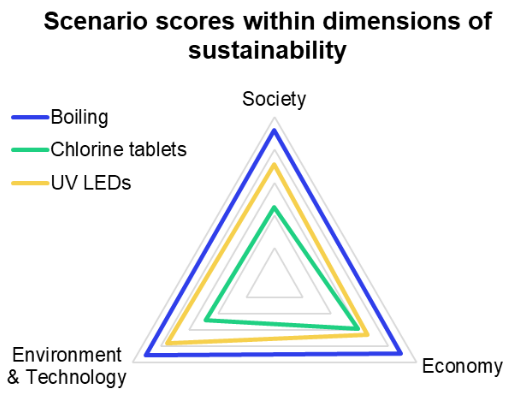


Figure 48. Scenario scores for each disinfection scenario normalized within dimensions of sustainability with respect to the maximum scorable value.

Even though this assessment was performed for disinfecting water intended for hygiene, scenarios are also promising for **household treatment of water intended for human consumption**.

The biggest limitations of UV-C LEDs - accessibility, relatively high investment cost, and requirement for training and a yearly control service - are possible to address on the regional or state level. This could potentially make them more suitable for application in Greenlandic settlements.

3.2.3 Key Findings on Greywater Recycling

Biologically Activated Gravity-Driven Membranes are suitable to operate in Greenland. However, they may be affected by lower temperatures in the Greenlandic households as the lowest flux was not found for the boundary temperatures of 5.0°C or 20.0°C but in the middle, at 12.5°C. No significant difference was found between membrane pre-seeding and its flux. The TOC results came to be inconclusive, therefore suitability of Greenlandic metazoan for membrane pre-seeding should be further investigated as well as nutrient-balancing, with expected nitrogen and phosphorous enrichment required for better carbon removal and enhanced disinfection with no by-products. Technology is almost energy-free and has low-cost operation but the potential vulnerability for handling greywater from other household sources, such as the kitchen, along with high initial cost and limited scalability must be addressed for successful application. In terms of Point-of-Use disinfection of recycled greywater, boiling remains the most favourable option based on the existing equipment and cultural acceptance that can be already implemented. UV-C LEDs show promise for long-term use if accessibility, including high initial cost, as well as training would be addressed. The most limited disinfection option for household level is the use of chlorine tablets as they lack not only cultural acceptance but also economic feasibility. Future studies should explore scalable technologies for recycling greywater from different household sources. They should also focus on local production from available materials to lower costs and increase accessibility.

4 Conclusions

The study highlights the need to address water storage practices in unpiped homes of Greenlandic settlements as **greywater reuse without treatment** remains a common practice. Greywater is finally discharged on the terrain, often delayed, especially in unpiped homes with no sinks with greywater outlets. Greywater storage units presented the highest levels of **microbial contamination (HPCs and total coliforms)** one level of magnitude higher than water intended for human consumption. Bacteria counts found in drinking water from household storage showed higher levels of contamination than those found in the water distribution system in the settlement. Water from the distribution system could be disinfected at the Point-of-Use, while greywater from washbasins would need **treatment before disinfection**.

The Biologically Activated Gravity-Driven Membrane shows **potential for use in Greenland** despite lower temperature affecting its performance, with the lowest flux observed at 12.5°C (~0.5 LMH). However, further research is required to investigate the suitability of Greenlandic metazoan for membrane pre-seeding as well as nutrient-balancing requirements. With the membrane system being energy- and cost-efficient in the long run, its **application is limited** to greywater from a single household source, it has a high initial cost and requires user training along with qualified personnel for maintenance performed every 6 to 12 months. Since treated water demonstrates bacteria counts exceeding the guideline limits from the Greenlandic Drinking Water Directive, water still **must be disinfected**. Owing to the high turbidity removal rates (93.89-98.33%), water is suitable also for turbidity-sensitive methods of disinfection. Nevertheless, with pH>8, the possibility of a decrease in the chlorination efficiency must be noted.

When selecting a method of disinfection at the household level, water safety, cultural acceptance, initial cost, access to equipment and supplies, operation & maintenance cost and safety of use must be considered along with other, less important criteria. Due to the existing equipment and high cultural acceptance, **boiling continues as the most favourable option**, followed by UV-C LEDs that show promise if accessibility and training were addressed, and chlorine tablets lacking both, acceptance and economic feasibility. Implementing these solutions could serve as a model for other remote Arctic communities facing similar challenges in the WASH sector.

Key findings on greywater treatment in the Arctic:

- High levels of microbial contamination found in water storage units,
- GDM technology demonstrated potential but requires further optimization,
- Boiling was identified as the favourable method of disinfection.

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Appendices

A. Fieldwork Data

Table A1. Microbial water quality parameters for samples from Itilleq, including results below the detection limit (BDL).

Nº	Date	Detailed location	HPC (37°C)	Total coliforms
			log CFU/1 mL	log CFU/100 mL
1.	05/09/2024	WTP outlet	BDL	BDL
2.	05/09/2024	WTP outlet	BDL	BDL
3.	05/09/2024	WTP outlet	BDL	BDL
4.	07/09/2024	Household A bathroom sink	BDL	BDL
5.	07/09/2024	Household A bathroom sink	BDL	BDL
6.	07/09/2024	Household A bathroom sink	BDL	BDL
7.	07/09/2024	Household A drinking water	1.4942	1.4472
8.	07/09/2024	Household A drinking water	1.0170	0.6021
9.	07/09/2024	Household A drinking water	1.1818	0.6021
10.	07/09/2024	Household B drinking water	1.0792	BDL
11.	07/09/2024	Household B drinking water	BDT	1.2041
12.	07/09/2024	Household B drinking water	1.0792	1.2041
13.	07/09/2024	Household B kitchen basin	2.9731	4.7924
14.	07/09/2024	Household B kitchen basin	3.0792	4.8195
15.	07/09/2024	Household B kitchen basin	3.0253	4.9445
16.	07/09/2024	Household C drinking water	1.0792	BDL
17.	07/09/2024	Household C drinking water	1.0792	1.2041
18.	07/09/2024	Household C drinking water	1.0792	1.2041
19.	07/09/2024	Household C kitchen basin	2.4771	4.1761
20.	07/09/2024	Household C kitchen basin	2.4771	4.1761
21.	07/09/2024	Household C kitchen basin	2.4771	4.1761
22.	07/09/2024	Household D bathroom basin	2.4771	4.1761
23.	07/09/2024	Household D bathroom basin	2.4771	4.1761
24.	07/09/2024	Household D bathroom basin	2.4771	4.1761
25.	07/09/2024	Household D drinking water	1.0792	BDL
26.	07/09/2024	Household D drinking water	1.0792	BDL
27.	07/09/2024	Household D drinking water	1.0792	BDL
28.	07/09/2024	Household E bathroom sink	BDL	BDL
29.	07/09/2024	Household E bathroom sink	BDL	BDL
30.	07/09/2024	Household E bathroom sink	BDL	BDL
31.	07/09/2024	Household E drinking water	BDL	BDL
32.	07/09/2024	Household E drinking water	BDL	BDL
33.	07/09/2024	Household E drinking water	BDL	BDL
34.	07/09/2024	Household F drinking water	1.0492	BDL
35.	07/09/2024	Household F drinking water	1.0792	BDL
36.	07/09/2024	Household F drinking water	1.0792	1.2041
37.	07/09/2024	Household F kitchen basin	2.9445	4.4771
38.	07/09/2024	Household F kitchen basin	2.8573	4.4472
39.	07/09/2024	Household F kitchen basin	2.9823	4.4472
40.	07/09/2024	Household G drinking water	1.0792	BDL
41.	07/09/2024	Household G drinking water	1.0792	2.7782

Nº	Date	Detailed location	HPC (37°C)	Total coliforms
			log CFU/1 mL	log CFU/100 mL
42.	07/09/2024	Household G drinking water	0.3945	2.1584
43.	07/09/2024	Household G kitchen basin	2.4771	4.1761
44.	07/09/2024	Household G kitchen basin	2.4771	4.1761
45.	07/09/2024	Household G kitchen basin	2.4771	4.1761
46.	07/09/2024	Household H bathroom basin	2.4771	4.1761
47.	07/09/2024	Household H bathroom basin	2.4771	4.1761
48.	07/09/2024	Household H bathroom basin	2.4771	4.1761
49.	07/09/2024	Household H drinking water	1.0792	1.9031
50.	07/09/2024	Household H drinking water	1.0792	1.9823
51.	07/09/2024	Household H drinking water	1.0792	1.2041
52.	09/09/2024	WTP outlet	BDL	BDL
53.	09/09/2024	WTP outlet	BDL	BDL
54.	09/09/2024	WTP outlet	BDL	BDL
55.	03/09/2025	Community Building	BDL	BDL
56.	03/09/2025	Service House	BDL	BDL
57.	09/09/2025	Taphouse 1 (well)	BDL	BDL
58.	09/09/2025	Taphouse 1 (well)	BDL	BDL
59.	09/09/2025	Taphouse 1 (well)	BDL	BDL
60.	09/09/2025	Taphouse 2 (centre)	BDL	BDL
61.	09/09/2025	Taphouse 2 (centre)	BDL	BDL
62.	09/09/2025	Taphouse 2 (centre)	BDL	BDL
63.	09/09/2025	Taphouse 3 (harbour)	BDL	BDL
64.	09/09/2025	Taphouse 3 (harbour)	BDL	BDL
65.	09/09/2025	Taphouse 3 (harbour)	BDL	BDL
66.	09/09/2025	Taphouse 4 (school)	BDL	BDL
67.	09/09/2025	Taphouse 4 (school)	BDL	BDL
68.	09/09/2025	Taphouse 4 (school)	BDL	BDL

Table A2. Physico-chemical water quality parameters for samples from Itilleq.

Nº	Date	Detailed location	Temperature	pH	Turbidity
			°C	-	NTU
1.	03/09/2024	Community Building	16.9	7.97	0.28
2.	03/09/2024	Community Building	17.0	7.97	0.27
3.	03/09/2024	Community Building	17.0	7.97	0.26
4.	03/09/2024	Service House	16.9	8.00	0.32
5.	03/09/2024	Service House	16.5	7.98	0.31
6.	03/09/2024	Service House	16.5	7.97	0.29
7.	05/09/2024	Taphouse 1 (well)	14.1	8.13	0.28
8.	05/09/2024	Taphouse 1 (well)	14.0	8.02	0.23
9.	05/09/2024	Taphouse 1 (well)	14.0	7.98	0.23
10.	05/09/2024	Taphouse 2 (centre)	12.8	7.99	0.37
11.	05/09/2024	Taphouse 2 (centre)	12.2	8.00	0.41
12.	05/09/2024	Taphouse 2 (centre)	12.3	8.01	0.33
13.	05/09/2024	Taphouse 3 (harbour)	14.9	8.07	0.42
14.	05/09/2024	Taphouse 3 (harbour)	14.9	8.05	0.39
15.	05/09/2024	Taphouse 3 (harbour)	15.1	8.05	0.38
16.	05/09/2024	Taphouse 4 (school)	13.8	8.04	0.38
17.	05/09/2024	Taphouse 4 (school)	13.7	8.01	0.35
18.	05/09/2024	Taphouse 4 (school)	13.7	8.00	0.38

Nº	Date	Detailed location	Temperature	pH	Turbidity
			°C	-	NTU
19.	05/09/2024	WTP outlet	14.8	8.04	0.29
20.	05/09/2024	WTP outlet	15.0	8.07	0.30
21.	05/09/2024	WTP outlet	15.1	8.07	0.31
22.	07/09/2024	Household A bathroom sink	17.3	7.48	9.99
23.	07/09/2024	Household A bathroom sink	17.3	7.44	9.99
24.	07/09/2024	Household A bathroom sink	17.3	7.41	9.99
25.	07/09/2024	Household B kitchen basin	17.3	7.92	9.99
26.	07/09/2024	Household B kitchen basin	17.7	7.86	9.99
27.	07/09/2024	Household B kitchen basin	18.0	7.84	9.99
28.	07/09/2024	Household C kitchen basin	16.7	7.06	1000
29.	07/09/2024	Household C kitchen basin	17.0	7.03	1000
30.	07/09/2024	Household C kitchen basin	17.6	7.02	1000
31.	07/09/2024	Household D bathroom basin	18.7	8.66	1000
32.	07/09/2024	Household D bathroom basin	18.1	8.68	1000
33.	07/09/2024	Household D bathroom basin	18.0	8.67	1000
34.	07/09/2024	Household E bathroom sink	17.5	8.18	0.48
35.	07/09/2024	Household E bathroom sink	17.5	8.10	0.5
36.	07/09/2024	Household E bathroom sink	17.6	8.07	0.5
37.	07/09/2024	Household F kitchen basin	18.0	7.26	9.99
38.	07/09/2024	Household F kitchen basin	18.1	7.24	9.99
39.	07/09/2024	Household F kitchen basin	18.2	7.22	9.99
40.	07/09/2024	Household G kitchen basin	17.9	6.54	9.99
41.	07/09/2024	Household G kitchen basin	18.0	6.51	9.99
42.	07/09/2024	Household G kitchen basin	17.8	6.49	9.99
43.	07/09/2024	Household H bathroom basin	17.0	7.62	9.99
44.	07/09/2024	Household H bathroom basin	17.5	7.59	9.99
45.	07/09/2024	Household H bathroom basin	18.0	7.56	9.99
46.	09/09/2024	Taphouse 1 (well)	10.5	8.07	0.34
47.	09/09/2024	Taphouse 1 (well)	10.2	8.04	0.32
48.	09/09/2024	Taphouse 1 (well)	10.8	8.02	0.21
49.	09/09/2024	Taphouse 2 (centre)	11.2	7.84	0.51
50.	09/09/2024	Taphouse 2 (centre)	9.3	7.98	0.49
51.	09/09/2024	Taphouse 2 (centre)	9.5	8.03	0.45
52.	09/09/2024	Taphouse 3 (harbour)	9.4	8.09	0.38
53.	09/09/2024	Taphouse 3 (harbour)	8.7	8.08	0.38
54.	09/09/2024	Taphouse 3 (harbour)	8.7	8.07	0.36
55.	09/09/2024	Taphouse 4 (school)	10.1	7.98	0.47
56.	09/09/2024	Taphouse 4 (school)	9.3	7.98	0.46
57.	09/09/2024	Taphouse 4 (school)	9.3	7.98	0.45
58.	09/09/2024	WTP outlet	11.2	7.63	0.55
59.	09/09/2024	WTP outlet	9.4	7.70	0.55
60.	09/09/2024	WTP outlet	9.1	7.88	0.55

B. Laboratory Experiments Data

Table B1. Membrane fluxes in LMH over time. Part 1 out of 2.

Nº	Day	**Flux**, LMH			
		5.0°C		**12.5°C**	
		clean	pre-seeded	clean	pre-seeded
1.	0	19.9334	20.1736	21.7384	21.0990
2.	1	3.1395	3.3834	2.6557	2.2388
3.	2	1.3973	1.4895	1.0785	1.0807
4.	3	1.1925	1.1934	0.7799	0.8913
5.	4	1.0634	1.0868	0.6655	0.7528
6.	5	1.0123	1.0123	0.5816	0.6800
7.	6	0.9627	0.9380	0.5193	0.6133
8.	7	0.8867	0.9120	0.4628	0.5473
9.	8	0.8663	0.8928	0.3913	0.5121
10.	9	0.8508	0.8478	0.4044	0.4246
11.	10	0.8352	0.8127	0.3873	0.4160
12.	11	0.7914	0.7909	0.3638	0.4090
13.	12	0.7788	0.7799	0.3638	0.3906
14.	13	0.7659	0.7659	0.3602	0.3602
15.	14	0.7170	0.7182	0.3754	0.3524
16.	15	0.7302	0.7076	0.3496	0.3493
17.	16	0.6563	0.6563	0.3186	0.3177
18.	17	0.6253	0.6249	0.3111	0.3109
19.	18	0.6296	0.6296	0.3142	0.3342
20.	19	0.1950	0.1950	0.2218	0.1745
21.	20	0.0916	0.0918	0.1546	0.1543
22.	21	0.0802	0.0748	0.1350	0.1350

Table B2. Membrane fluxes in LMH over time. Part 2 out of 2.

Nº	Day	**Flux**, LMH			
		20.0°C		**CONTROL**	
		clean	pre-seeded	clean	pre-seeded
1.	0	22.0948	33.0222	18.1064	21.1463
2.	1	3.2758	3.5098	19.5972	21.9393
3.	2	1.8141	1.8153	18.6742	21.5472
4.	3	1.4338	1.4348	16.6693	19.9903
5.	4	1.2386	1.2620	13.4883	15.4784
6.	5	1.0594	1.0829	7.9341	8.4531
7.	6	0.9402	0.9395	6.4595	6.1883
8.	7	0.8388	0.8394	4.5916	5.6386
9.	8	0.7909	0.7953	5.1481	6.0566
10.	9	0.7400	0.7374	6.3339	7.1741
11.	10	0.6777	0.6785	7.4066	7.4127

Nº	Day	**Flux**, LMH			
		20.0°C		**CONTROL**	
		clean	pre-seeded	clean	pre-seeded
12.	11	0.6436	0.6180	7.7664	7.3095
13.	12	0.5902	0.5926	8.1914	7.6738
14.	13	0.5870	0.5853	8.1986	7.9731
15.	14	0.5916	0.8093	7.6955	6.7905
16.	15	0.5940	0.6587	7.9616	7.1502
17.	16	0.5582	0.6130	7.9331	7.4373
18.	17	0.5047	0.5497	7.6745	7.1998
19.	18	0.4788	0.5217	8.0634	7.6204
20.	19	0.2393	0.2393	5.4036	5.1507
21.	20	0.2363	0.2474	4.6855	4.6885
22.	21	0.2147	0.2429	4.6870	4.6870

Table B3. Fouling layer hydraulic resistances in m^{-1}over time. Part 1 out of 2.

Nº	Day	**Fouling layer hydraulic resistance**, m^{-1}			
		5.0°C		**12.5°C**	
		clean	pre-seeded	clean	pre-seeded
1.	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.	1	2.88E+03	2.64E+03	4.44E+03	5.36E+03
3.	2	7.15E+03	6.68E+03	1.18E+04	1.18E+04
4.	3	8.47E+03	8.47E+03	1.66E+04	1.44E+04
5.	4	9.56E+03	9.35E+03	1.96E+04	1.72E+04
6.	5	1.01E+04	1.01E+04	2.25E+04	1.91E+04
7.	6	1.06E+04	1.09E+04	2.52E+04	2.12E+04
8.	7	1.16E+04	1.12E+04	2.84E+04	2.39E+04
9.	8	1.19E+04	1.15E+04	3.37E+04	2.56E+04
10.	9	1.21E+04	1.21E+04	3.26E+04	3.10E+04
11.	10	1.23E+04	1.27E+04	3.40E+04	3.16E+04
12.	11	1.30E+04	1.31E+04	3.63E+04	3.22E+04
13.	12	1.33E+04	1.32E+04	3.63E+04	3.37E+04
14.	13	1.35E+04	1.35E+04	3.66E+04	3.66E+04
15.	14	1.44E+04	1.44E+04	3.51E+04	3.75E+04
16.	15	1.42E+04	1.46E+04	3.78E+04	3.78E+04
17.	16	1.58E+04	1.58E+04	4.15E+04	4.16E+04
18.	17	1.66E+04	1.67E+04	4.25E+04	4.25E+04
19.	18	1.65E+04	1.65E+04	4.21E+04	3.95E+04
20.	19	5.45E+04	5.46E+04	5.99E+04	7.63E+04
21.	20	1.17E+05	1.17E+05	8.62E+04	8.64E+04
22.	21	1.33E+05	1.43E+05	9.88E+04	9.88E+04

Table B4. Fouling layer hydraulic resistances in m^{-1}over time. Part 2 out of 2.

Nº	Day	**Fouling layer hydraulic resistance**, m^{-1}			
		20.0°C		**CONTROL**	
		clean	clean	clean	clean
1.	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.	1	4.25E+03	4.16E+03	-6.86E+01	-2.79E+01
3.	2	8.27E+03	8.50E+03	-2.74E+01	-1.44E+01
4.	3	1.07E+04	1.09E+04	7.78E+01	4.47E+01
5.	4	1.25E+04	1.25E+04	3.09E+02	2.83E+02
6.	5	1.47E+04	1.46E+04	1.16E+03	1.16E+03
7.	6	1.66E+04	1.69E+04	1.63E+03	1.87E+03
8.	7	1.87E+04	1.90E+04	2.66E+03	2.12E+03
9.	8	1.99E+04	2.00E+04	2.27E+03	1.92E+03
10.	9	2.13E+04	2.17E+04	1.68E+03	1.50E+03
11.	10	2.34E+04	2.36E+04	1.30E+03	1.43E+03
12.	11	2.46E+04	2.59E+04	1.20E+03	1.46E+03
13.	12	2.69E+04	2.71E+04	1.09E+03	1.36E+03
14.	13	2.71E+04	2.74E+04	1.09E+03	1.28E+03
15.	14	2.69E+04	1.97E+04	1.22E+03	1.63E+03
16.	15	2.68E+04	2.43E+04	1.15E+03	1.51E+03
17.	16	2.85E+04	2.62E+04	1.16E+03	1.42E+03
18.	17	3.16E+04	2.92E+04	1.23E+03	1.50E+03
19.	18	3.34E+04	3.08E+04	1.12E+03	1.37E+03
20.	19	6.75E+04	6.78E+04	2.12E+03	2.40E+03
21.	20	6.84E+04	6.55E+04	2.58E+03	2.71E+03
22.	21	7.53E+04	6.67E+04	2.58E+03	2.71E+03

Table B5. Heterotrophic Plate Count at 22°C in samples from each experimental line, including results below the detection limit (BDL).

Nº	Source	**HPC (22°C)**				
		Log CFU/1 mL				
		Day 4	**Day 8**	**Day 12**	**Day 16**	**Day 20**
1.	5°C, feed water	2.4771	2.4771	2.4771	2.4771	2.4771
2.	5°C, clean	2.4771	2.4771	2.4771	2.4771	2.4771
3.	5°C, pre-seeded	2.4771	2.4771	2.4771	2.4771	2.4771
4.	12.5°C, feed water	2.4771	2.4771	2.4771	2.4771	0.4771
5.	12.5°C, clean	2.4771	2.4771	2.4771	2.4771	2.3674
6.	12.5°C, pre-seeded	2.4771	2.4771	2.4771	2.4771	0.7782
7.	20.0°C, feed water	2.4771	2.4771	2.4771	2.4771	2.4771
8.	20.0°C, clean	2.4771	2.4771	2.4771	2.4771	2.4771
9.	20.0°C, pre-seeded	2.4771	2.4771	2.4771	2.4771	2.4771
10.	CONTROL, feed water	2.4771	2.4771	2.4771	2.4771	0.6990
11.	CONTROL, clean	2.4771	2.4771	2.4771	2.4771	1.1139
12.	CONTROL, pre-seeded	2.4771	2.4771	2.4771	2.4771	0.9542

Table B6. Total coliforms in samples from each experimental line, including results below the detection limit (BDL).

Nº	Source	Total coliforms Log CFU/100 mL				
		Day 4	Day 8	Day 12	Day 16	Day 20
1.	5°C, feed water	4.1761	4.1761	4.1761	4.1761	4.1761
2.	5°C, clean	4.1761	2.6021	4.1761	4.1761	4.1761
3.	5°C, pre-seeded	BDL	3.5911	4.1761	4.1761	4.1761
4.	12.5°C, feed water	4.1761	4.1761	4.6232	4.1761	4.1761
5.	12.5°C, clean	BDL	3.6812	3.3802	4.1761	4.1761
6.	12.5°C, pre-seeded	BDL	2.0000	BDL	2.9031	4.1761
7.	20.0°C, feed water	4.1761	4.1761	4.1761	4.1761	4.1761
8.	20.0°C, clean	BDL	4.1761	4.1761	4.1761	4.1761
9.	20.0°C, pre-seeded	BDL	4.1761	4.1761	4.1761	4.1761
10.	CONTROL, feed water	BDL	BDL	BDL	BDL	2.1761
11.	CONTROL, clean	BDL	BDL	BDL	BDL	2.1761
12.	CONTROL, pre-seeded	BDL	BDL	BDL	BDL	2.1761

Table B7. Physico-chemical water quality parameters for samples from each experimental line with the mean value, ± standard deviation and number of samples (n).

Nº	Detailed location	Temperature	pH	Turbidity
		°C	-	NTU
1.	5.0°C greywater	20.0	7.73 ±0.13 (3)	20.73 ±0.83 (3)
2.	5.0°C clean	20.0	8.50 ±0.09 (3)	0.46 ±0.1 (3)
3.	5.0°C pre-seeded	20.0	8.40 ±0.04 (3)	0.47 ±0.11 (3)
4.	12.5°C greywater	20.0	7.54 ±0.06 (3)	27.00 ±0.9 (3)
5.	12.5°C clean	20.0	8.40 ±0.13 (3)	1.65 ±0.18 (3)
6.	12.5°C pre-seeded	20.0	8.54 ±0.41 (3)	0.45 ±0.05 (3)
7.	20.0°C greywater	20.0	7.55 ±0.15 (3)	28.27 ±1.03 (3)
8.	20.0°C clean	20.0	8.45 ±0.03 (3)	0.61 ±0.04 (3)
9.	20.0°C pre-seeded	20.0	8.27 ±0.02 (3)	1.50 ±0.05 (3)
10.	20.0°C tap water (CONTROL)	20.0	8.41 ±0.01 (3)	1.69 ±0.03 (3)
11.	20.0°C clean (CONTROL)	20.0	8.79 ±0.09 (3)	0.03 ±0.01 (3)
12.	20.0°C pre-seeded (CONTROL)	20.0	8.72 ±0.14 (3)	0.11 ±0.02 (3)

Table B8. Total Organic Carbon in permeate samples from each experimental line.

Nº	Detailed location	Day 17	Day 21
		mgTOC/L	mgTOC/L
1.	5.0°C clean	206.2	61.7
2.	5.0°C pre-seeded	81.3	66.0
3.	12.5°C clean	84.4	73.6
4.	12.5°C pre-seeded	81.5	78.9
5.	20.0°C clean	172.7	14.3
6.	20.0°C pre-seeded	216.6	149.1
7.	20.0°C clean (CONTROL)	5.6	4.5
8.	20.0°C pre-seeded (CONTROL)	1.3	15.9

C. Katadyn Micropur Forte Tablets

KATADYN®
MAKING WATER DRINKING WATER

FACT SHEET

MICROPUR FORTE TABLETS - disinfects and conserves water effectively

PRODUCT CHARACTERISTICS

Active substances:	Troclosene sodium 99.8 mg/g, Silver 1.8 mg/g All ingredients used are permissible for use in drinking water
Effect:	Eliminates bacteria* and viruses* in 30 minutes Amoebas and giardia* in 120 minutes. Conserves drinking water for up to 6 months
Dosage:	See reverse
Materials:	Can be used in plastic or glass. Check metals before use
Notes on safety:	See reverse
Storage:	Store in original packaging in a dry place under 25°C
Shelf-life:	5 years from date of manufacture

* see test results on backside

FACTS

- Micropur Forte disinfects clear water and keeps it germ-free for up to 6 months.
- Due to the strong oxidizing power of chlorine, most protozoa and fungi are eliminated as well as bacteria and viruses.
- Micropur Forte can be used wherever microbiologically unsafe water requires disinfection (e.g. drinking, cooking washing).
- It is also ideal for conserving water in water tanks, water baths, air conditioning systems, heating systems, humidifiers, wells, incubators and more.
- For clear, not for cloudy water as suspended matter can weaken the effect of chlorine and silver ions. Use a Katadyn Microfilter for cloudy water.

PRODUCT CHARACTERISTICS > BENEFITS

- Contains chlorine > disinfects water
- Contains silver ions > preserves water for up to 6 months
- Small and handy packaging > will fit everywhere

SHORT PROFILE

Water disinfection and conservation. Ideal for treating water while travelling.

1

KATADYN
MAKING WATER DRINKING WATER

FACT SHEET

MICROPUR FORTE TABLETS - disinfects and conserves water effectively

PRODUCT FORM

Art. No.	Product form	Capacity	Dosage
Micropur Tablets:			
8014258	Micropur Forte MF 1T (D/E/F/NL/IT)	100 tablets	1 tablets for 1 l, treats 100 l
8013662	Micropur Forte MF 1T (ES/DK/SE/NO/FI)	100 tablets	1 tablets for 1 l, treats 100 l
8017906	Micropur Forte MF 1T (EN/PL/CZ/HU/RUS)	100 tablets	1 tablets for 1 l, treats 100 l

USE

Micropur Tablets

Use one Micropur Forte tablet for one litre of clear water; wait 10 minutes until the tablet has dissolved; shake well; wait another 20 minutes before using the water.

Further tips:

- If the water is very cold or you are concerned about the possible presence of Giardia cysts in the water, allow two hours wait time.
- The max. amount of silver in drinking water is 0.1 mg/l and is not exceeded once Micropur Forte has taken full effect.
- Use Mircopur Antichlorine to neutralise the (light) taste of chlorine.

Safety

In case of contact with eyes, rinse immediately with water.
Use biocides safely. Always read the label and product information before use.

TESTS (Effectiveness of chlorine)

Mark D. Sobsey, Taksahi Fuji, Patricia A. Shields, 1988.
Pathogenes examined: Hepatitis A HM175, Coxsackievirus B5, Coliphages ATCC 13706-B1

Rice et al., 1982. Pathogenes examined: Giardia lamblia cysts, Giardia muris cysts

Katadyn reserves the right to modify product characteristics

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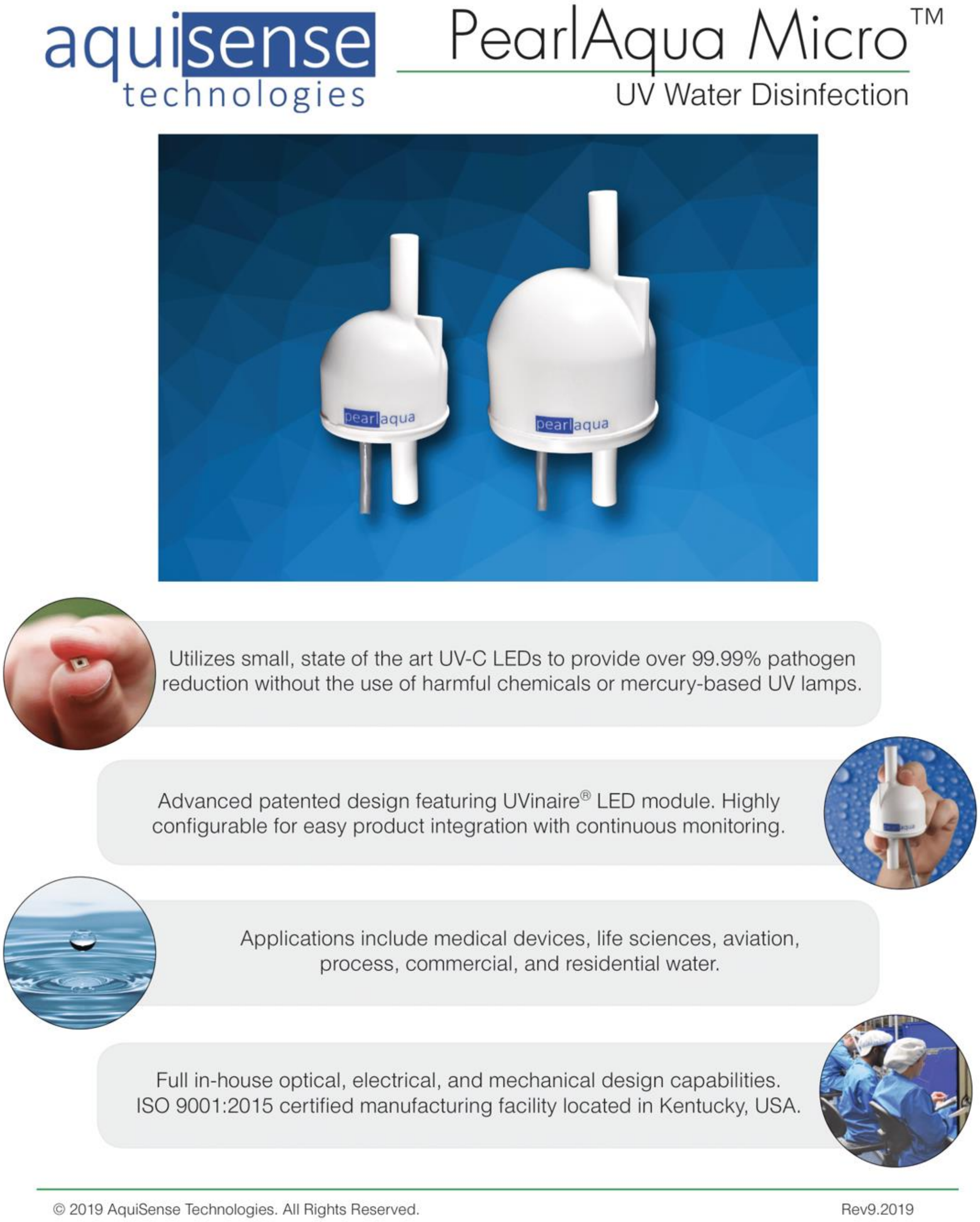
2

D. Pearl Aqua Micro™



aquisense technologies

PearlAqua Micro™

UV Water Disinfection

FEATURES	
Mercury Free	Low Power Consumption
Remote Start/Stop	Unlimited On/Off Cycling
Instantaneous On	Thermal Monitoring
Consistent Performance Across Water Temperature Range	

OPTIONS
UV Intensity Monitoring (C Only)
LED Status Output
Power Cable Length and Connector
Mounting Bracket

SPECIFICATIONS

Specifications provided as a guide. Variations possible based on customer requirements.

Product Name			PearlAqua Micro			
Model Number			3B	6B	9C	12C
Max Flow[1] [lpm (gpm)]	UV Dose (mJ/cm²)	10	1.2 (0.3)	2.0 (0.5)	5.3 (1.4)	8.0 (2.1)
		16	0.9 (0.24)	1.5 (0.4)	4.0 (1.1)	5.0 (1.3)
		40	0.25 (0.07)	0.50 (0.13)	1.75 (0.5)	2.25 (0.6)
Headloss at Max Flow [mbar (psi)]			65 (0.9)	165 (2.4)	407 (5.9)	917 (13)
Inlet/Outlet Water Connection			Male: 3/8", 11mm, or other		Male: 3/8", 1/2", or other	
Weight [g (oz)]			77 (2.7)		162 (5.7)	
Max Operating Pressure[2] [bar (psi)]			8.3 (120)			
Environmental Protection			IP68			
Lamp Life[3] [hours]			up to 10,000			
Max Ambient Temp [°C (°F)]			80 (176)			
Fluid Temperature [°C (°F)]			0-50 (32-122)		0-45 (32-113)	
Electrical Connection			4-Core Cable, 150 mm (6") length			
Input Voltage [V DC]			12 or 24		12	
Input Power[3] [W]			2.5 - 4	5 - 8	7 - 11	9 - 14

NOTES

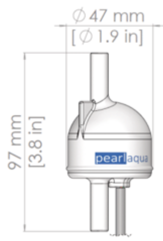
[1] 3rd party bioassay tested with T1 Phage and MS-2 Phage at 98% UV-T with reference to 254 nm

[2] 3rd party tested at 2.4x greater, 19.8 bar (288 psi) at temperature 19 °C (67 °F)

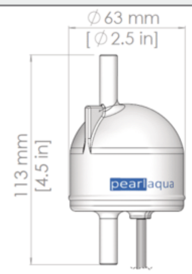
[3] Dependent on product configuration and application

Specifications subject to change

B DIMENSIONS



C DIMENSIONS



CE RoHS IUVA REACH ISO

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4400 Olympic Blvd Erlanger, KY 41018 USA

E. Calculations for Disinfection Scenarios

Boiling

$$T_B = V \cdot t_B = 18{,}980\ L \cdot 2.5\ min \cdot \frac{1\ h}{60\ min} = 791\ h \qquad \text{(E1)}$$

$$E_B = V \cdot E_{B,1} \cdot \frac{1}{\eta} = 18{,}980\ L \cdot 0.092\ \frac{kWh}{L} \cdot \frac{1}{0.8} = 2{,}182.7\ kWh \qquad \text{(E2)}$$

$$C_E = E_B \cdot p = 2{,}182.7\ kWh \cdot 1.87 \frac{DKK}{kWh} = 4{,}082\ DKK \qquad \text{(E3)}$$

Where:
T_B - boiling time over 1 year, h,
V - the volume of water disinfected over 1 year = 18,980 L,
t_B - boiling time of 1 L of water = 2.5 min[1],
E_B - energy required for boiling over 1 year, kWh,
$E_{B,1}$ - energy required to bring 1 L of water in room temperature to boiling = 0.092 kWh/L[2],
η - electric kettle efficiency = 0.8[2],
C_E - energy cost for boiling over 1 year, DKK,
p - price of energy unit = 1.87 DKK/kWh.

Chlorine tablets NaDCC

$$C_C = \frac{p}{n} \cdot V = \frac{220\ DKK}{100\ L} \cdot 18{,}980\ L = 41{,}756\ DKK \qquad \text{(E4)}$$

Where:
C_C - chlorine tablets cost over 1 year, DKK,
p - price for package = 220 DKK[3],
n - disinfected water equivalents per package = 100 L[3],
V - the volume of water disinfected over 1 year = 18,980 L.

[1] A. Coerver *et al.*, *Compendium of Water Supply Technologies in Emergencies*. Malteser International, 2021. Accessed: Jan. 18, 2025. [Online]. Available: https://www.humanitarianlibrary.org/sites/default/files/2022/09/GWN_Emergency-Water-Compendium_2021_new.pdf

[2] SeeSustainability, "Boiling water - how much energy?" Accessed: Jan. 23, 2025. [Online]. Available: https://seesustainability.co.uk/blog/f/boiling-water---how-much-energy

[3] Sisimiut Outdoor "Katadyn Micropur Forte MF1 (4x25) Desinficerer drikkevand" Accessed: Jan. 23, 2025. [Online]. Available: https://sisimiutoutdoor.gl/shop/29-outdoorudstyr--outdoor-equipments--asimi-atortut/208785-katadyn-micropur-forte-mf1-4x25-desinficerer-drikkevand/

UV-C LEDs

$$T_{UV} = \frac{V}{Q_{max}} = \frac{18{,}980\ L}{0.25\ \frac{L}{min}} \cdot \frac{1\ h}{60\ min} = 1{,}265.3\ h \quad \text{(E5)}$$

$$E_{UV} = T_{UV} \cdot P = 1{,}265.3\ h \cdot 3.25\ W = 4{,}112\ Wh \approx 4.1\ kWh \quad \text{(E6)}$$

$$C_{UV} = E_{UV} \cdot p = 4.1\ kWh \cdot 1.87 \frac{DKK}{kWh} = 7.7\ DKK \quad \text{(E7)}$$

$$L_{UV} = \frac{LRI}{T_{UV}} = \frac{10{,}000\ h}{\frac{1{,}265.3\ h}{1\ year}} = 7.9\ years \quad \text{(E8)}$$

Where:
T_{UV} - time of UV treatment over 1 year, h,
V - the volume of water disinfected over 1 year = 18,980 L,
Q_{max} - the maximum flow at UV-dose of 40 mJ/cm^2 = 0.25 L/min (Appendix D),
E_{uv} - energy required for UV treatment over 1 year, kWh,
P - average maximum input power = $\frac{2.5+4}{2}$ = 3.25 W (Appendix D),
C_{UV} - energy cost for the use of UV over 1 year, DKK,
p - price of energy unit = 1.87 DKK/kWh,
L_{UV} - lifespan of UV lamps, years,
LRI - lamp replacement interval = 10,000 h (Appendix D).