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Feasibility assessment on sand utilization from wastewater treatment plants

Test material from Klettagarðar and Ánanaust

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Abstract

This report is part of an ongoing work towards implementation of a circular economy in the operation of Veitur sewage system, thereby eliminating disposal of waste, especially biodegradable waste. This report summarizes the results of experiments carried out between March 2022 and September 2023 and seeks to answer whether it is practical and safe to utilize the residual sand from the wastewater treatment plants in Klettagarðar and Ánanaust for the company's construction projects, such as sanding along pipes. This is followed up with a comprehensive Life Cycle Assessment (LCA) which compares sand sourced from treatment plants versus from a quarry, to evaluate the environmental impacts and benefits.

Subject words Fráveita, sandur, hringrásarhagkerfi, endurnýting, Klettagarðar, Ánanaust, hreinsistöð	Reviewed by HSÞ

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1 Introduction

Veitur, in cooperation with the Research and Innovation Department of Orkuveita Reykjavíkur, applied for and received a grant from Ministry of the Environment, Energy and Climate to assess the feasibility of using sand from sewage treatment plants in the capital area.

The project is part of the implementation of a circular economy in the operation of Veitur sewage systems, thereby eliminating disposal of waste, especially biodegradable waste. This report summarizes the results of experiments carried out between March 2022 and September 2023 and seeks to answer whether it is practical and safe to utilize the residual sand from the wastewater treatment plants for the company’s construction projects, such as sanding along pipes. This is followed up with a comprehensive Life Cycle Assessment (LCA) which compares sand sourced from treatment plants versus from a quarry, to evaluate the environmental impacts and benefits.

2 Background

Veitur fulfills the statutory role of providing residents in the municipalities in Reykjavík, Akranes, and Borgarbyggð with access to sewage. In Reykjavík there are three preliminary treatment plants, at Klettagarðar, Ánanaust and Kjalarnes. There screening waste, sand and fat is separated from the wastewater before it is discharged 4-5 km out into Faxaflói. The materials cleaned from the wastewater come in separated streams, one of which is sand collected in containers for disposal.

Sewage in Veitur’s preliminary treatment plants in Reykjavík, Kjalarnes, Akranes and Borgarnes is routed through two steps of treatment: coarse screening and grit removal, figure 1. Screening refers to the removal of coarse solids, larger than 3 mm, that may be floating or suspended within the wastewater. Typically, these solids will consist of wet wipes, plastics, rubber, fabric material, and vegetable remains. The water particles, sand and many other contaminants are small enough to pass through this filter.

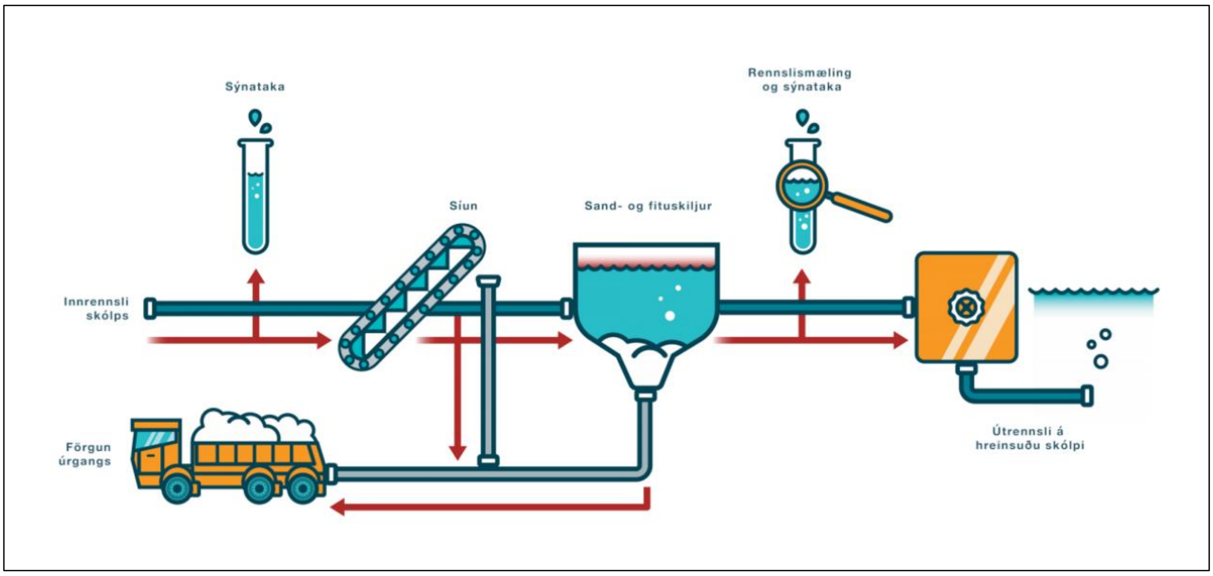

Figure 1. Diagram of the cleaning cycle of Veitur wastewater treatment plants in Reykjavík, Kjalarnes, Akranes and Borgarnes.

The next step is grit removal where small solid particles, such as sand and grit, are removed from the wastewater mixture. The water is allowed to settle and small particles with a high mass relative to the particles around them are gravity-sorted, i.e., gravity causes them to sink to the bottom of the sand settling basin. Some of the grease and organic materials are also floated off.

The sand is then washed in a sand washing machine before it is collected in a sand container in the waste collection space of the sewage treatment plants, from where it is currently collected for disposal at a landfill. The sand washing machine can be seen in figure 2, and the cleaned sand after washing in figure 3.

Figure 2. Sand washing machine in Veitur wastewater treatment plant in Klettagarðar.

Figure 3. Cleaned sand in the waste collection area of Veitur wastewater treatment plant in Klettagarðar.

A seasonal variation is detected in the amount of sand passing through the wastewater treatment plants. The amounts of sand slightly higher during the winter season compared to the summer months, probably due to the sanding the pavements in slippery conditions and the wear of street surfaces.

The graph in figure 4 shows the trend in the amount of washed sand from Veitur's largest sewage treatment plants, the treatment plants at Ánanaust and Klettagarðar in Reykjavík. On average for the last 9 years the total amount of washed sand is 100 - 200 tons yearly. The amount of sand from Klettagarðar and Ánanaust in 2023 presented in the graph only represents the first 11 months of the year.

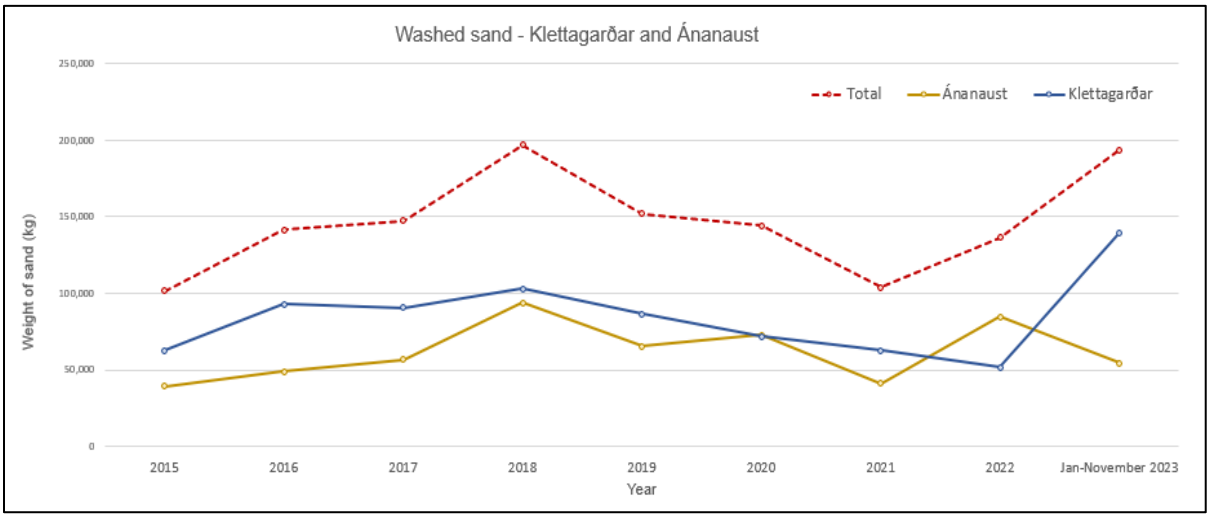

Figure 4. Graph of the yearly amount of washed sand deposited from the wastewater treatment plant in Klettagarðar and Ánanaust.

Common unit prices for purchased sand for construction sites are approximately 3 ISK per kilogram (ref: Burðarlag | 0-22 mm | Eden | Björgun (bjorgun.is)). The unit price that Veitur pays for the disposal of sand from the treatment plants in Reykjavík was in September this year is 21.88 ISK per kilogram with VAT, which is about 2.2 to 4.4 million ISK per year.

3 Methods

3.1 The experimental procedure

The aim for the setup of the experiments was to keep it simple, low budged, non-added chemical and reproduceable on a larger scale. The setup was to fill up containers with washed sand from the treatment plants in Klettagarðar and Ánanaust and place them outside for storage every two months, twelve containers in total (figure 5, table 1). The strategy was to collect samples of the washed sand covering the whole year to be able to detect any seasonal variations in the composition of the sand in terms of microbial quantity, chemical concentration, particle size and/or thermal conductivity. The variability should be observed if sampling was evenly distributed over the year.

Figure 5. Containers with washed sand from both wastewater treatment plants were lined up at Klettagarðar where they were stored during the experimental period.

Containers were deployed simultaneously from Klettagarðar and Ánanaust, evenly distributed over the year 2022, i.e., in March, May, June, September and January 2023 (table 1). When the containers were deployed, samples were collected for both microbiological and chemical analyses. In addition, temperature probes were placed in the sand. To begin with, samples were also taken for geotechnical tests, but this was soon ceased as our service provider was unable to carry out the analysis due to the odor that erupted during the analytical procedure. Geotechnical testing was therefore only performed on three samples at the end of the experimental period, when microbial concentrations had diminished in the material. Microbiological samples were collected approximately every second week until values reached at least below 1000/gr and most often below 100/gr. Then the second chemical sample from each container was collected by the end of the experimental period to get a comparison to the chemical concentration of the samples at the start of the experiment.

Table 1. Dates when containers were deployed and their assigned number.

Date	**Klettagarðar** Container number	**Ánanaust** Container number
04.03.2022	1	
31.03.2022	2	3
10.05.2022	4	5
24.06.2022	6	7
28.09.2022	8	9
13.01.2023	10	11

During the storage experimental period reconstructions were made on the sewage treatment plant in Klettagarðar. The screens used to filter out all material >3mm were not fully effective due to a high age; letting material larger than 3 mm through the cleaning step and were thus replaced for new ones. After the renewal of the screens, there turned out to be a visible difference between the material that reached the containers, see figure 6. The containers filled before renewal had frequent obstacles of nonmineral origin larger than 3 mm, whereas the sand after reconstruction did not visually contain nonmineral material. Only container 10 contains sand originated after screens renewal.

Figure 6. On the left is sand before screen change and on the right is sand after screen change, noticeably absent of >3mm material.

3.2 Life cycle assessment method

The Life Cycle Assessment (LCA) method is based on the International Reference Life Cycle Data System (ILCD) handbook and standards published by the International Organization for Standardization (ISO), specifically ISO 14040 (ISO 14040:2006, Environmental management,Life cycle assessment, Principles and framework, 2006) and ISO 14044 (ISO 14044:2006, Environmental management, Life cycle assessment, Requirements and guidelines, 2006). The ILCD handbook (European Platform on LCA | EPLCA, 2010) and the ISO standards set forth four main phases of the LCA method.

The first phase of LCA is the goal and scope definition (figure 7). This is a definition of why the LCA is being conducted, what the expected outcome of the LCA is, how deep and far the LCA and its inventory go, and what stages of a product's life cycle are included in the assessment, from raw material extraction up to disposal. The functional unit is defined along with the system boundaries.

Second is a life cycle inventory analysis. A broad but detailed overview of the input and output data of the assessment. A list and quantities of processes within the system boundary on which the whole product system was built and scaled up. Validation and qualification of the data collected are also presented. Combining and allocating the data with the actual processes used for LCA.

Third is a Life cycle impact assessment. A life cycle impact assessment is aimed at giving a conclusion and overview of the environmental impacts caused by each process within the system boundary. A selection and a presentation of the indicators and categories used to describe and compare the different systems are shown.

The fourth and final phase of the LCA method is the life cycle interpretation: In this phase, all findings compared and considered in making a conclusion that should reflect and fulfill the goal and scope of the LCA. Additional recommendations, notes and possible issues should be presented to provide an understandable and well-rounded conclusion that represents the goal and scope.

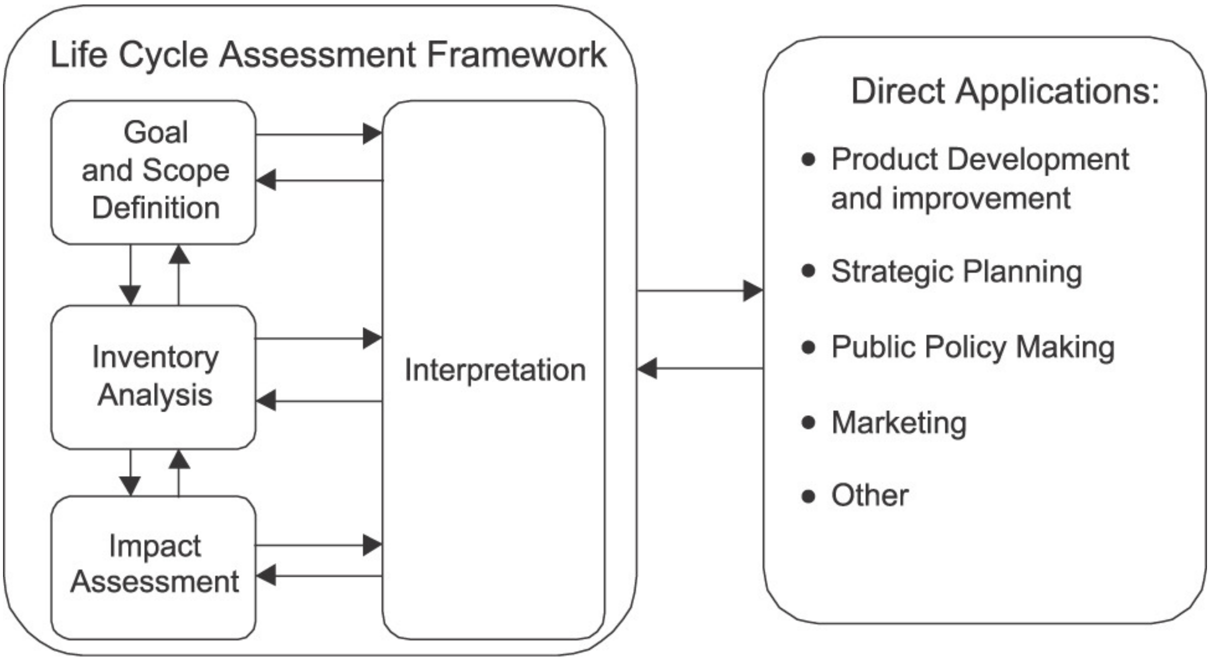

Figure 7. Life cycle assessment explanation (Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications, 2004)

4 Analysis results

4.1 Geotechnical testing

The geotechnical tests proved to be hard to conduct due to odor during the analytical procedure. Thus, the number of samples was adapted to 3 samples in total instead of 22 samples, two from each container at the start and end date, as was done with the chemical sampling.

After some weeks, when organic material and microbiota had diminished, the odor had subsided, and a geotechnical test was feasible to conduct. Container 1 was chosen to represent material before renewal of the screens in Klettagarðar and container 10 represents material after the screen change. Container 11 is from the Ánanaust wastewater treatment plant.

4.1.1 Grain size analyses

Grain size analysis was performed on samples before and after the renewing of the screening equipment. One sand sample was analyzed from container 1 taken before the renewal in Klettagarðar and one sample from container 11 in Ánanaust. One sample was taken from container deployed after renewing the filters, from Klettagarðar container 10. Figure 8 shows results from the grain size distribution. Table 2 and figure 8 demonstrate that most of the material is categorized as medium sand and falls inside the limits for ideal grain size distribution for sanding e.g. along electrical cables or pipes. However, for sanding electrical cables grain size distribution is not the only factor that needs to be accounted for, thermal conductivity is important as well.

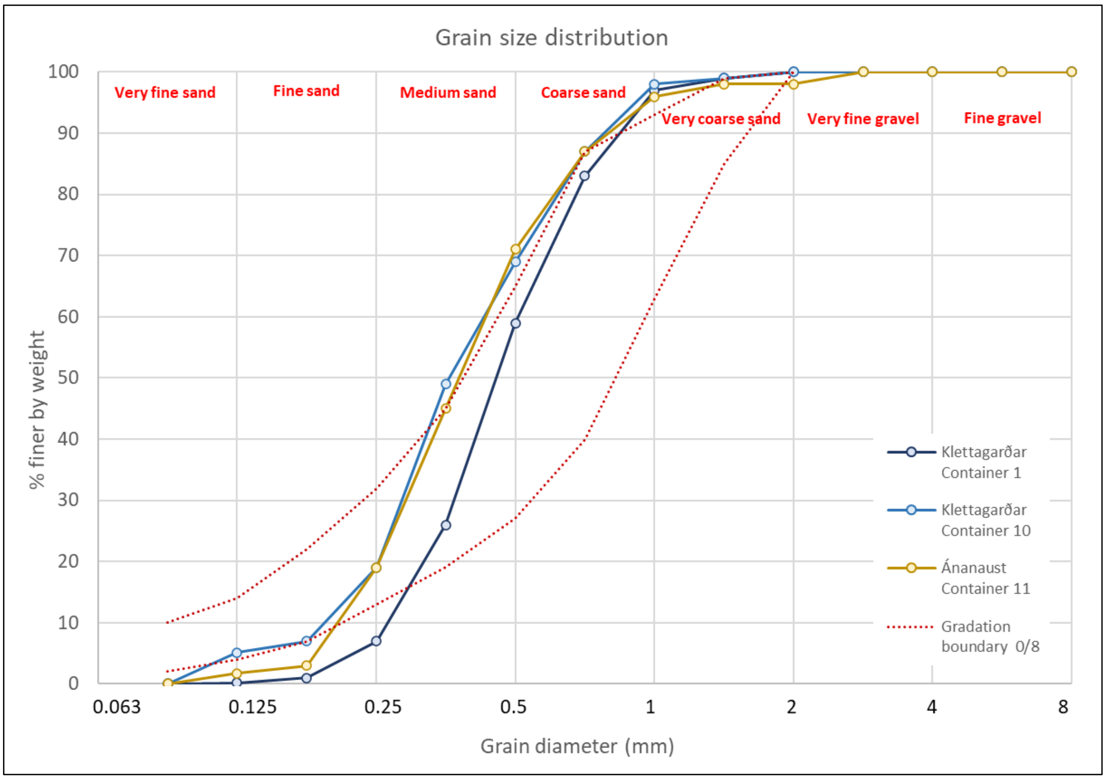

Figure 8. Grain size distribution on samples from Klettagarðar container 1 and 10 and Ánanaust container 11. The dotted red line represents 0/8 boundaries for ideal grain size distribution for sanding electrical cables.

In table 2 the results of the technical matters of the grain size analysis are listed. The uniformity coefficient (C_u), curvature coefficient (C_c) and the effective size (D_{10}) are the grading characteristics of the sample. These are the geometric properties of the grading curve that describe the sample type. The uniformity coefficient (C_u) expresses the variety in particle sizes of the sand and is defined as the ratio of D_{60} to D_{10}. The value D_{60} is the grain diameter at which 60% of the sand particles are finer and 40% of the sand particles are coarser, while D_{10} is the grain diameter at which 10% of particles are finer and 90% of the particles are coarser. Values greater than 4 are classified as well graded, whereas C_u values less than 4 are more uniform. The coefficient of curvature C_c should lie between 1 and 3 for well-graded sample. The slope of the gradation curve of the sample gives the coefficient of curvature which represents the shape of the particle size distribution curve.

Table 2. Technical matters in grain size analyses.

Technical matters	Klettagarðar Container 1	Klettagarðar Container 10	Ánanaust Container 11
D_{10}	0.27	0.15	0.17
D_{15}	0.33	0.2	0.21
D_{30}	0.54	0.32	0.33
D_{50}	0.83	0.52	0.57
D_{60}	1.04	0.73	0.75
D_{85}	2.18	1.83	1.85
C_u*	3.79	4.91	4.52
C_c**	1.02	0.95	0.89

*The coefficient of uniformity / **The coefficient of curvature

The results on the technical matters on the washed sand samples from the three containers are variable and not straight forward to interpret. The sand sample from container 1, before screen renewal, is poorly graded according to C_u and C_c values. Whereas the samples from containers 10 and 11 are well graded according to the C_u value, however the C_c value indicates rather uniform grading.

4.1.2 Thermal conductivity

The main thermal characteristics of soil are thermal conductivity and thermal resistance. Conductivity measurements on the sand sample describe the sand properties which govern the flow of heat through the sand. If the sand were to be used as a filling material for electrical cables, then the sand needs to provide high thermal conductivity allowing heat to flow easily from the cables. In that aspect the ratio between bedrock material, organic matter, water and air is particularly important. Bedrock material being better for the purpose of conducting heat than organic matter and water is better for the purpose than air. Thus, grading is important to be able to compact the material better. Those factors being less important in the case of the sand being used as a filling material for wastewater pipes rather than for electrical cables.

Figure 9 shows a graph of the thermal resistance versus humidity. Ideally samples should plot along or below the dotted line to be suitable for sanding along electrical cables. The sample in container 1 has the lowest thermal resistance and thus better for the purpose of being a filling material for electrical cables. However, if compared to a reference curve from Bolungarvík, containing ideal filling material for electrical cables, values from container 1 are above the boundaries and thus not suitable.

The sample after the screen renewal has a higher ratio of organic matter and thus can easily absorb moisture and thus has even higher thermal resistance and is not as suitable for the purpose of filling material for electrical cables.

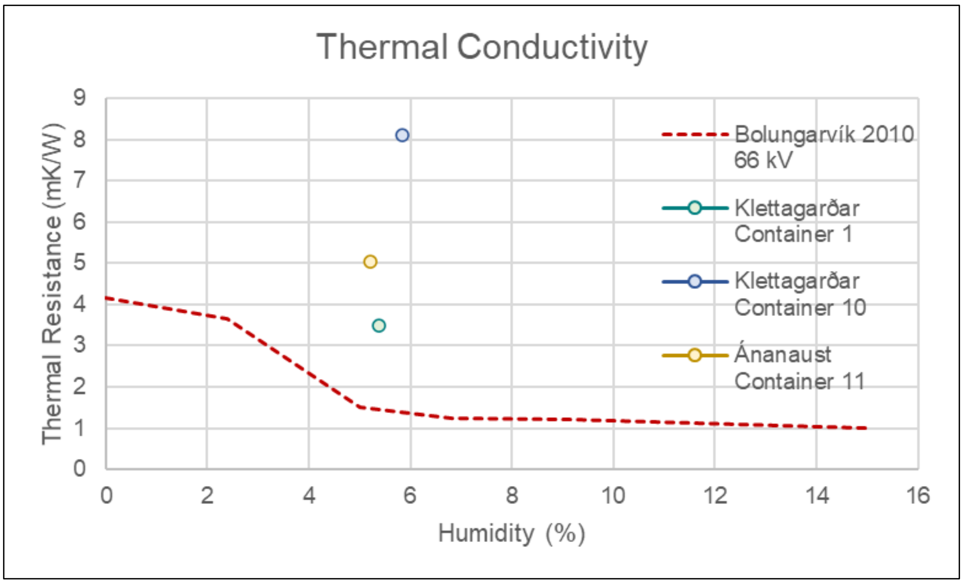

Figure 9. Samples from containers 1, 10 and 11 are shown on a thermal conductivity graph along with a reference curve from Bolungarvík, red dotted line. Preferably samples should plot below the red dotted line to be suitable as a filling material for electrical cables.

4.2 Microbial measurements

The growth and survival of coliforms and enterococci are dependent on biotic and abiotic stress factors. Abiotic stressors are e.g., temperature, water and nutrient availability, salinity, pH and solar radiation. Biotic factors include the presence of other micro-organisms and the ability of coliforms and enterococci to acquire nutrients, competing with other microorganisms. Coliforms and enterococci are facultative anaerobic bacteria and can thus survive in both oxygen-rich and oxygen-poor environments. However, coliforms are versatile in their ability to obtain energy and only require simple carbon and nitrogen sources, whereas enterococci have more complex nutrient requirements (Ishii, et.al., 2008 and Byappanahalli, et.al., 2012).

Table 3. Overview of when the microbial levels in each container reach below 250/gr.

Ánanaust Container no.	Number of days bacterial count reached below 250/gr	Klettagarðar Container no.	Number of days bacterial count reached below 250/gr
		1	111
3	511	**2**	181
5	471 (cocci still at 840/gr)	**4**	189
7	258	**6**	96
9	331	**8**	331 (coliform still at 430/gr)
11	56 (cocci still at 340/gr)	**10**	56

Sand samples were taken from the containers as they were deployed to analyze the microbial load in the washed sand. The number of heat-resistant coliforms and fecal cocci was measured per gram. Without exception, the highest values were measured when the containers were put out, and the microbial count usually decreased during storage. The highest value measured was the initial sample from container 3 from Ánanaust, where heat-resistant coliforms were measured at 24,000,000/gr.

It took the longest, 511 days, to bring the microbial count down to 250/gr in container 3 from Ánanaust (table 3). On average, it took longer to bring down the microbial levels in containers from Ánanaust compared to Klettagarðar. In container 10 from Klettagarðar, taken after screen renewal, it took only 56 days (less than two months) for microbiota to fall below 100/gr. Eight containers out of 11 reached below 250/gr by the end of the experimental storage period. For the purposes of further analyses, we assume one year for Klettagarðar and one and a half to two years for Ánanaust to be sufficient storage time for the washed sand before it can be reutilized. According to the work scenario in chapter 5 the washed sand will be assumed to be utilized as a filling material along wastewater pipes. Water running through the sand could potentially be contaminated by microbials, although it will be further filtered by soil before potentially being able to reach surface waters.

The Environment Agency in Iceland publishes regulations with threshold limits for contamination. It is not completely clear under what regulation reutilization of washed wastewater sand should be compared to, but the Environmental Agency suggests as a first order assumption to follow threshold limits in Regulation 796/1999 on prevention of water pollution (Reglugerð um varnir gegn mengun vatns 796/1999, with more recent amendments). The environmental limits for microbial contamination in surface water from outdoor activities are divided into five categories (table 4). Results are also compared to regulation 1400/2020 on contaminated soil (Reglugerð um mengaðan jarðveg 1400/2020).

Table 4. Five categories are published in Regulation on prevention of water pollution 796/1999.

Environmental limits	I	II	III	IV	V
Coliforms or enterococci/100ml	<14	14-100	100-200	200-1000	>1000

The next figures 10 and 11 represent the decrease of bacteria in all containers from Klettagarðar and Ánanaust during the experimental storage period.

Generally, stressors such as **sunlight, salinity, disinfection, starvation** and **predation** will lead to a decline in the population over time (Byappanahalli et al., 2012). According to working scenarios in chapter 5 the washed sand will be stored in an open pile of sand where **sunlight** will act as a stressor decreasing the number of bacteria at the surface of the pile. Presently, no **disinfection** processes are included in the cleaning process of the treatment plants. The most common disinfection strategy for wastewater is the utilization of chlorine followed by UV light irradiation. This process could be worth evaluating in the future although further chemical intervention is not necessarily feasible.

The transition from the nutrient-rich sewage system to a storage pile will in time enhance nutrient **starvation** for the bacterial population. Starvation is the most significant stressor affecting the washed sand during the experimental storage period. Lastly, **predation** by bacteria and how the bacteria compete with other microorganisms is also a stressor that cannot be ignored. However, further discussion is beyond the scope of this study.

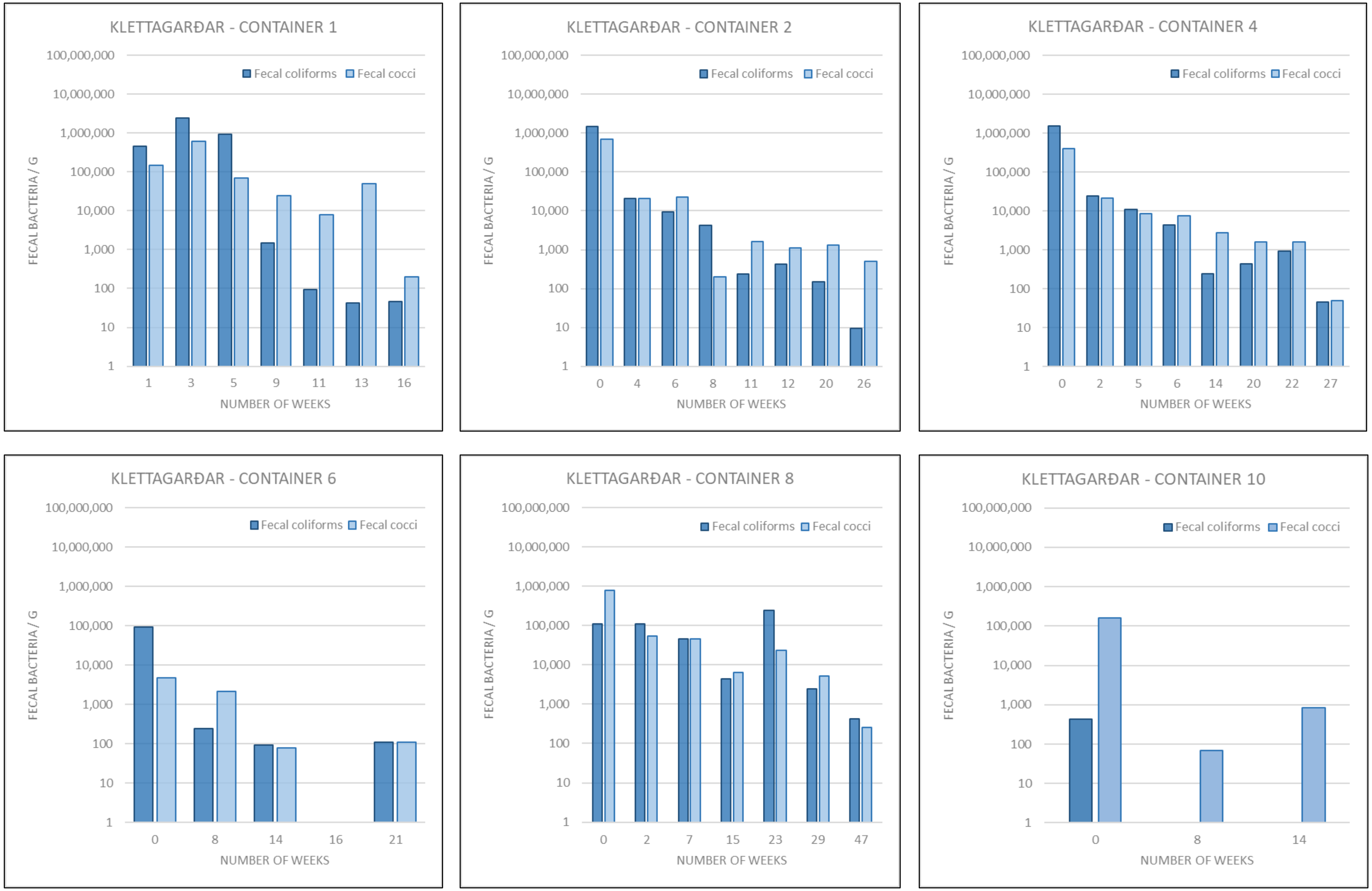

Figure 10. All sand containers from Klettagarðar and development of the number of bacteria in each container during the experimental period.

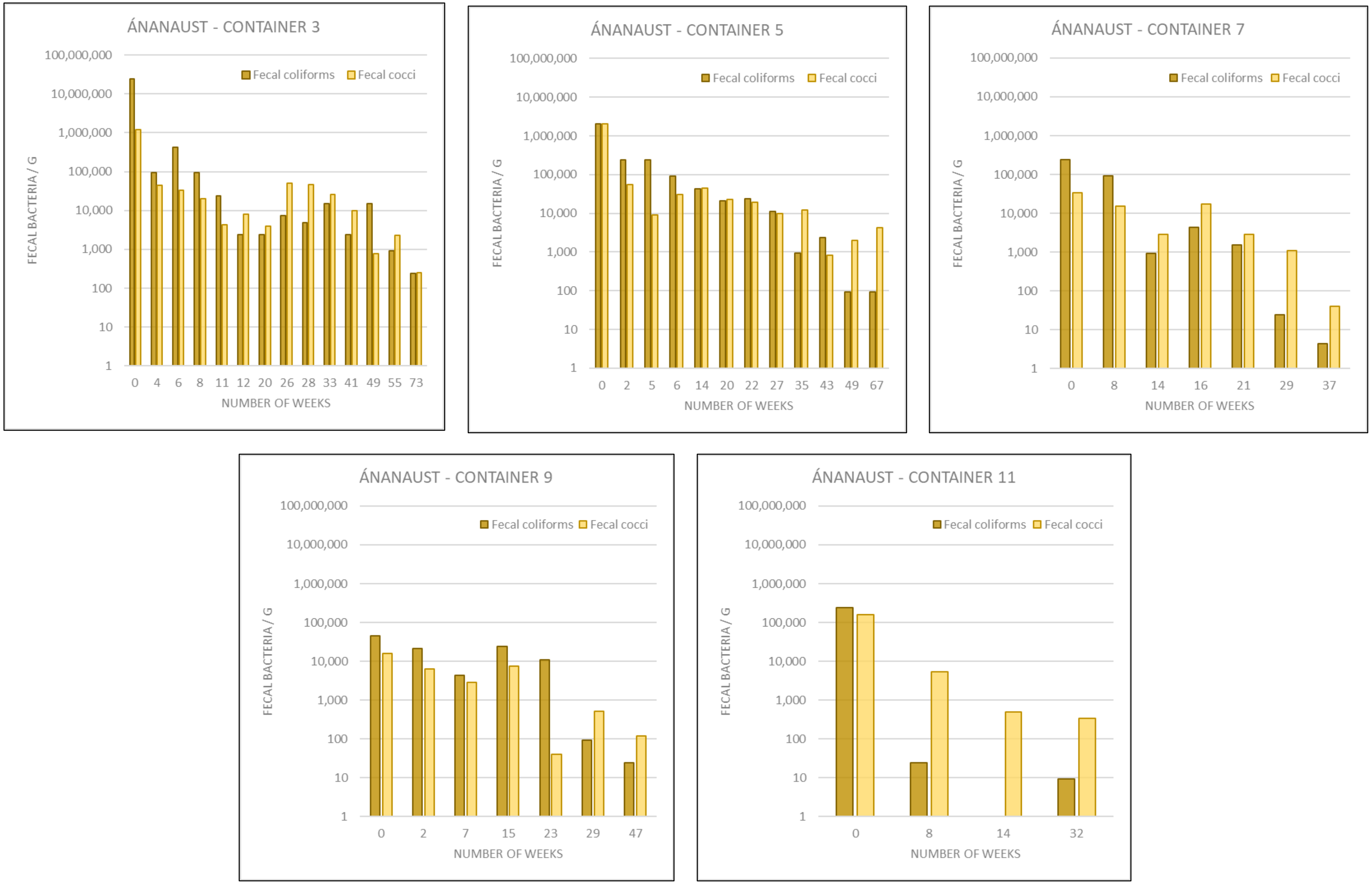

Figure 11. All sand containers from Ánanaust and development of the number of bacteria in each container during the experimental storage period.

Figures 12 and 13 compare containers from Klettagarðar (figure 12) and Ánanaust (figure 13) and the number of days it takes fecal coliforms to decrease below the two boundary limits from the regulations 796/1999 and 1400/2020. Blue colors represent containers from Klettagarðar and orange colors represent containers from Ánanaust. The results show that in all containers the number of fecal coliforms fall below the upper limit (1000/g) from regulation 1400/2020. Moreover, results also show that fecal coliforms decrease faster below the limits in Klettagarðar compared to Ánanaust. All values from all containers fall below the lower limit (100/g) from regulation 796/1999 except one from container 8, which still contained 430 heat resistant coliforms per gram by the end of the experimental period.

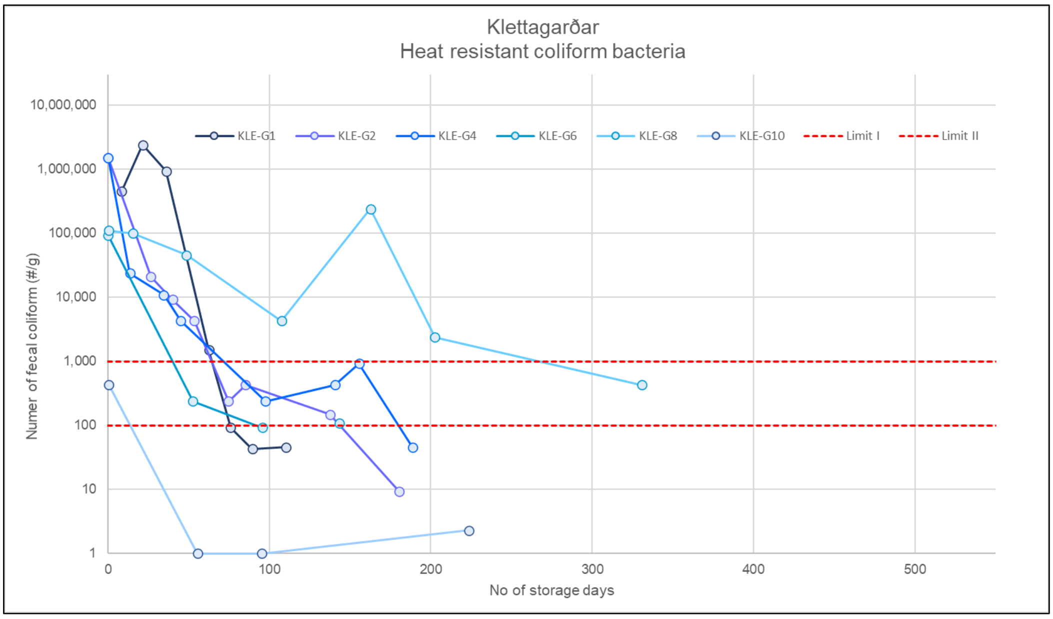

Figure 12. Number of fecal coliforms in all containers from Klettagarðar.

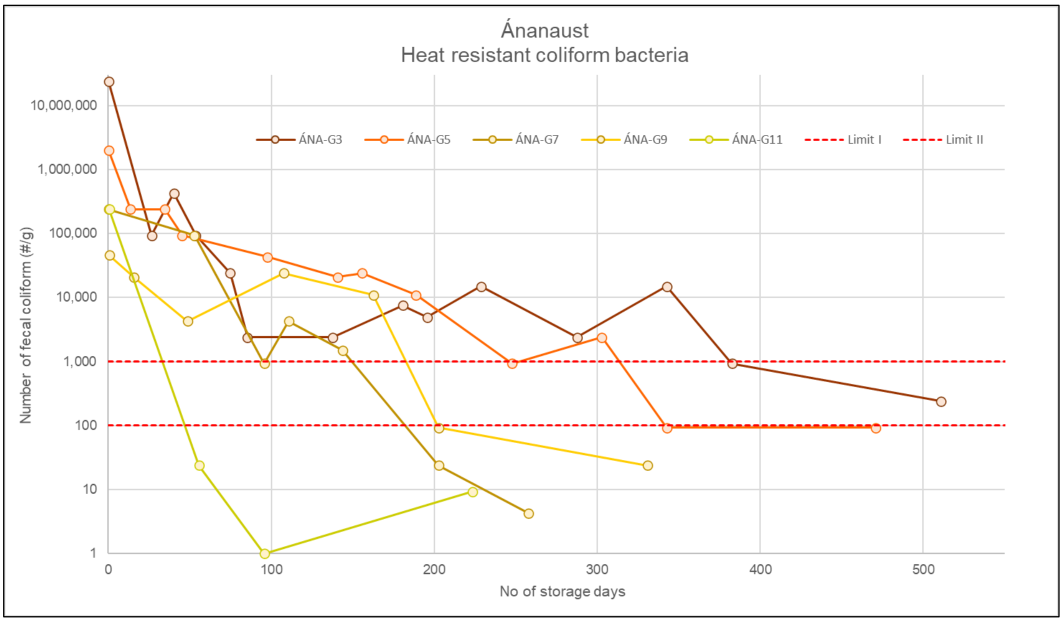

Figure 13. Number of fecal coliforms in all containers from Ánanaust.

In figure 14 and 15 containers from Klettagarðar and Ánanaust are compared and the number of days it takes fecal cocci to decrease below the two boundary limits from the regulations 796/1999 and 1400/2020. Results show that the number of fecal cocci from all containers from Klettagarðar and Ánanaust fall below the upper limit (1000/g) except for container 5 from Ánanaust. Furthermore, results indicate that also the fecal cocci decreased faster below the limits in Klettagarðar compared to Ánanaust. Opposite to the results for fecal coliforms, only samples from three containers fall below the limit of 100 cocci per gram for Klettagarðar and two for Ánanaust.

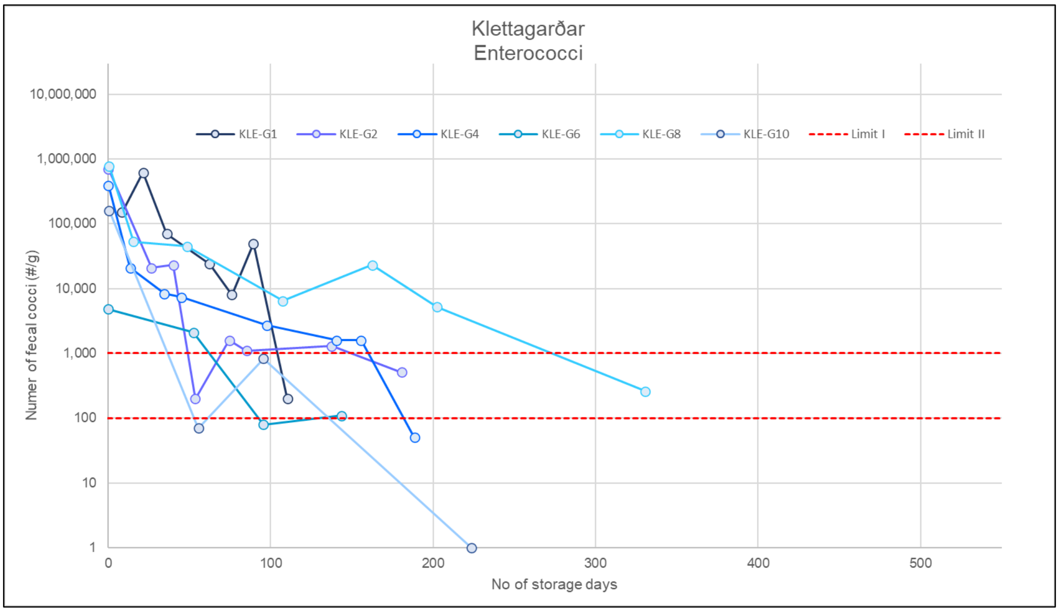

Figure 14. Number of fecal cocci in all containers from Klettagarðar.

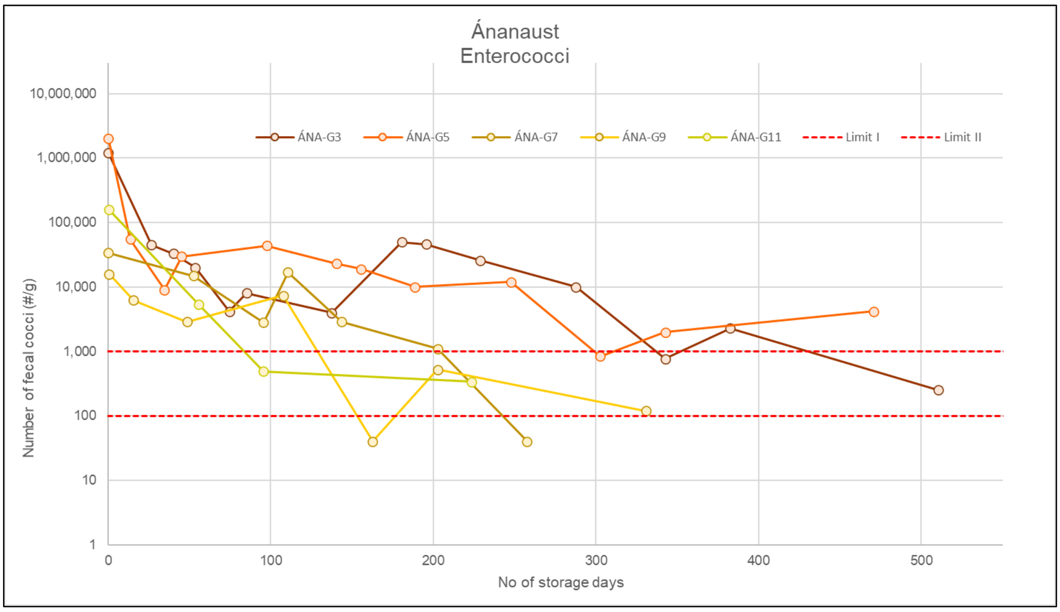

Figure 15. Number of fecal cocci in all containers from Ánanaust.

Thus, fecal bacteria decrease faster from Klettagarðar compared to Ánanaust most likely due to the sand from Ánanaust being richer in organic matter. Of the two fecal bacteria, coliform and cocci, the coliform decreases faster. Thus, fecal coliforms in containers from Klettagarðar decrease the fastest and fecal cocci from Ánanaust the slowest.

4.2.1 Temperature effect on coliforms and fecal cocci

Temperature and temperature fluctuations are one of the abiotic factors influencing the growth and survival rate of Coliforms and Enterococci fecal bacteria. Thus, temperature loggers were placed in the washed sand in all containers during the experimental storage period. In figure 16, a combined temperature graph is illustrated from all the temperature loggers. Also, the number of microbiotas, coliforms and fecal cocci, from container 3 are plotted for comparison. No specific correlation is seen in the temperature data and in the steadily decreasing microbiota. Even though the temperature went below 0°C during the storage period, December 2022- February 2023, the death rate of the bacteria stayed approximately the same.

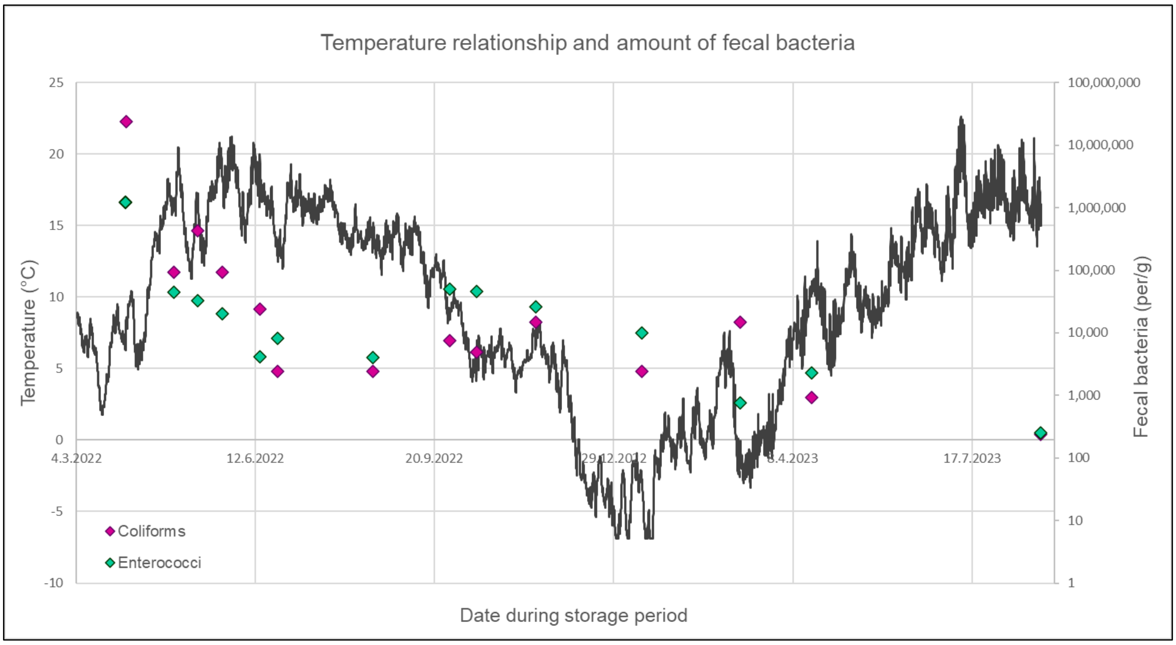

Figure 16. Black line shows combined temperature graph from temperature loggers from all containers. Purple and green diamonds represent amounts of Coliforms and Enterococci per gram in container 3. No relationship is seen between the temperature and decrease in the number of bacteria.

This is further demonstrated in table 5 showing the percentual change of the number of fecal bacteria between sampling analysis. The microbial amount decreases and, in few cases, increases rather randomly with no correlation to temperature changes. The temperature change in the experimental storage period spans -7 to 23°C. Temperature values higher than 60°C are more likely to have an effect. This suggests that nutrients are more of a limiting factor rather than temperature.

Table 5. The number of fecal bacteria in container 3 from Ánanaust and change in % between sampling intervals.

Date	Coliforms (#/g)	Cange (%)	Enterococci (#/g)	Cange (%)
31.3.2022	24,000,000		1,200,000	
27.4.2022	93,000	-100	45,000	-96
10.5.2022	430,000	362	33,000	-27
24.5.2022	93,000	-78	20,000	-39
14.6.2022	24,000	-74	4,200	-79
24.6.2022	2,400	-90	8,100	93
16.8.2022	2,400	0	4,000	-51
28.9.2022	7,500	213	50,000	1150
13.10.2022	4,900	-35	46,000	-8
15.11.2022	15,000	206	26,000	-43
13.1.2023	2,400	-84	10,000	-62
9.3.2023	15,000	525	770	-92
18.4.2023	930	-94	2,300	199
24.8.2023	240	-74	250	-89

4.3 Chemical analysis

Chemical analyses were performed on sand samples from all containers as they were deployed for storage. The sand containers were then stored for a few months and after storage another sand sample was taken for chemical analysis for comparison.

During the experimental storage period the washed sand dehydrates in the containers. On average slightly higher dehydration in Klettagarðar, lowering of 14% compared to 11% in containers from Ánanaust (table 6).

Table 6. Percent of dry matter in the sand samples at the start of storage and at the end.

Ánanaust			Klettagarðar		
Container	Start date Dry matter (%)	End date Dry matter (%)	Container	Start date Dry matter (%)	End date Dry matter (%)
			1	87.2	92.1
3	87.8	97.6	2	84.8	97.8
5	73.3	95.6	4	79.0	96.0
7	76.3	84.2	6	92.6	98.3
9	83.8	89.9	8	77.3	92.9
11	85.0	96.7	10	55.9	83.1

As previously mentioned in chapter 4.2 there is no specific regulation for reutilization of sand from wastewater treatment plants and thus only suggested threshold limits for contamination for comparison. Results of the chemical analysis are therefore compared to threshold limits in Regulation 799/1999 on sludge treatment (Reglugerð um meðhöndlun seyru) and Regulation 1400/2020 on contaminated soil (Reglugerð um mengaðan jarðveg) (table 7; lower limit in 1400/2020 is for soil as residential land use and upper limit is for land use for commercial areas). The aim of the assessment is that all values after storage will be under those limits. The

Environmental Agency also suggests acknowledging regulation 796/1999 on prevention on water pollution (Reglugerð um varnir gegn mengun vatns). The boundary limits in table 7 are shown for different categories of pollution from I-V, those are much stricter than in regulation 799/1999 and 1400/2020. It must be noted that our work theory is that the reutilized sand will be used along wastewater pipes and leaching from it will travel through soil before entering open water bodies. Samples from those water bodies would rightfully be appropriate for comparison to those limits from the regulation on prevention on water pollution. Those strictest limits are shown in table 7 and figure 17 and 18, the less strict limits in regulation 799/1999 and 1400/2020 are not shown on those figures since they are out of scale and values well below the limits.

Inorganic trace elements/heavy metals (As, Pb, Cd, Cr, Cu, Ni, Hg, Ag and Zn) can be of concern for public health because of toxic effects at low intake levels or to the environment. Results from chemical analysis on sand from all containers show values well below limits of concern, table 8. According to the work scenario in chapter 5 the washed sand will be utilized as a filling material along wastewater pipes. Water running through it may thus be further filtered by soil before potentially being able to contaminate surface waters.

Table 7. Preliminary environmental limits based on three regulations: 799/1999, 1400/2020 and 796/1999.

	Reglugerð um meðhöndlun seyru 799/1999	**Reglugerð um mengaðan jarðveg 1400/2020**		**Reglugerð um varnir gegn mengun vatns 796/1999**				
	Limit mg/kg	***Limit mg/kg**	****Limit mg/kg**	**I**	**II**	**III**	**IV**	**V**
Arsenic (As) mg/kg		27	76	0.0004	0.005	0.015	0.075	>0.075
Lead (Pb) mg/kg	50-300	210	530	0.0002	0.001	0.003	0.015	>0.015
Cadmium (Cd) mg/kg	1-3	1.2	4.3	0.00001	0.0001	0.0003	0.0015	>0.0015
Chromium (Cr) mg/kg		130	180	0.0003	0.005	0.015	0.075	>0.075
Copper (Cu) mg/kg	50-140	100	190	0.0005	0.003	0.009	0.045	>0.045
Nickel (Ni) mg/kg	30-75	160	200	0.0007	0.015	0.045	0.225	>0.225
Mercury (Hg) mg/kg	1-1.5	0.83	4.8					
Silver (Ag) mg/kg								
Zinc (Zn) mg/kg	150-300	200	270	0.005	0.02	0.06	0.3	>0.300

* Max values for residential land use mg/kg dry matter / ** Max values for commercial area land use mg/kg dry matter

The origin of all Icelandic soils is volcanic, consisting mostly of volcanic glass and eolian sediments (Arnalds, O., 2004). The sand deposited in the Icelandic wastewater system is largely composed of soil, sand and other material washed of the streets and thus has high concentration of heavy metals such as Ni, Cd, Cr and Cu compared to the Nordic and European countries. Boundary limits from the EU are thus not ideal to compare to.

Arsenic (As), as the other following heavy metals, can be a pollutant in the biosphere if it accumulates in plants or animals. The detection limit in this study is <0.01 mg/kg. All start samples from both Klettagarðar and Ánanaust had concentration below category V (Regulation 796/1999).

In most cases As concentration was lowered during storage (table 7,8 and figure 17). After storage As was detected in only two containers from Klettagarðar and two from Ánanaust. In only one container (2) values were higher after storage.

The detection limit of Cadmium (Cd) in this study is <0.003 mg/kg and is not detected in any of the start containers except container 10 from Klettagarðar, 0.006 mg/kg. After storage Cd is not detected in any of the containers.

The detection limit for Chromium (Cr) in this study is <0.01 mg/kg and is detected in 7 out of 11 containers that were deployed, with the highest value in container 10, 0.31 mg/kg. After storage Cr was only detected in containers from Klettagarðar and in very low concentration, or around category III in regulation 796/1999.

The boundary limits for Copper (Cu) in regulation 796/1999 are very low as can be seen in figure 17. Cu concentration in all the start containers is well above those limits. In Klettagarðar the end values tend to be higher than the start values. The detection limit for Cu in this study is <0.05 mg/kg.

The detection limit for Lead (Pb) in this study is <0.01 mg/kg. The EU boundary limit for it in soil is 60 mg/kg. However, the highest Pb concentration, 0.73 mg/kg, found in this study was in container 10 at the start of the storage. After storage for 220 days the Pb concentration had lowered below the detection limit. All measured values are below the limits in regulation 1400/2020 on contaminated soil (210 mg/kg). After storage all values in the containers from Ánanaust are below detection limit, the highest concentration after storage in Klettagarðar are found in container 2 and 6, 0.03 mg/kg which would place them in category V >0.015 mg/kg in regulation 796/1999 for contaminated water.

Sources of nickel (Ni) in wastewater include cruise ship effluents, industrial applications, and the chemical industry. In this study Ni was found in all containers at the start from Klettagarðar and Ánanaust, with the highest concentration seen in container 10 from Klettagarðar, 1.12 mg/kg. In most cases Ni concentration was lowered during storage below the limit for category V in regulation 796/1999, except for in container 2, 6 and 7. The detection limit for Ni in this study is <0.01 mg/kg.

Mercury (Hg) enters wastewater from a variety of sources including dental practice wastes, fertilizers and paints. The detection limit of Hg in this study is <0.002 mg/kg and is only detected in one sample, 0.003 mg/kg.

Zinc (Zn) in wastewater sand can in some portions be traced to car tires. Zn is detected in all containers at the start of the storage with the highest concentration, 12.2 mg/kg in container 10 from Klettagarðar. Noticeably the value is lowered to 0.3 mg/kg after storage. The containers from Klettagarðar contain higher values after storage opposed to containers from Ánanaust that contain lower values after storage. The detection limit for Zn in this study is <0.01 mg/kg.

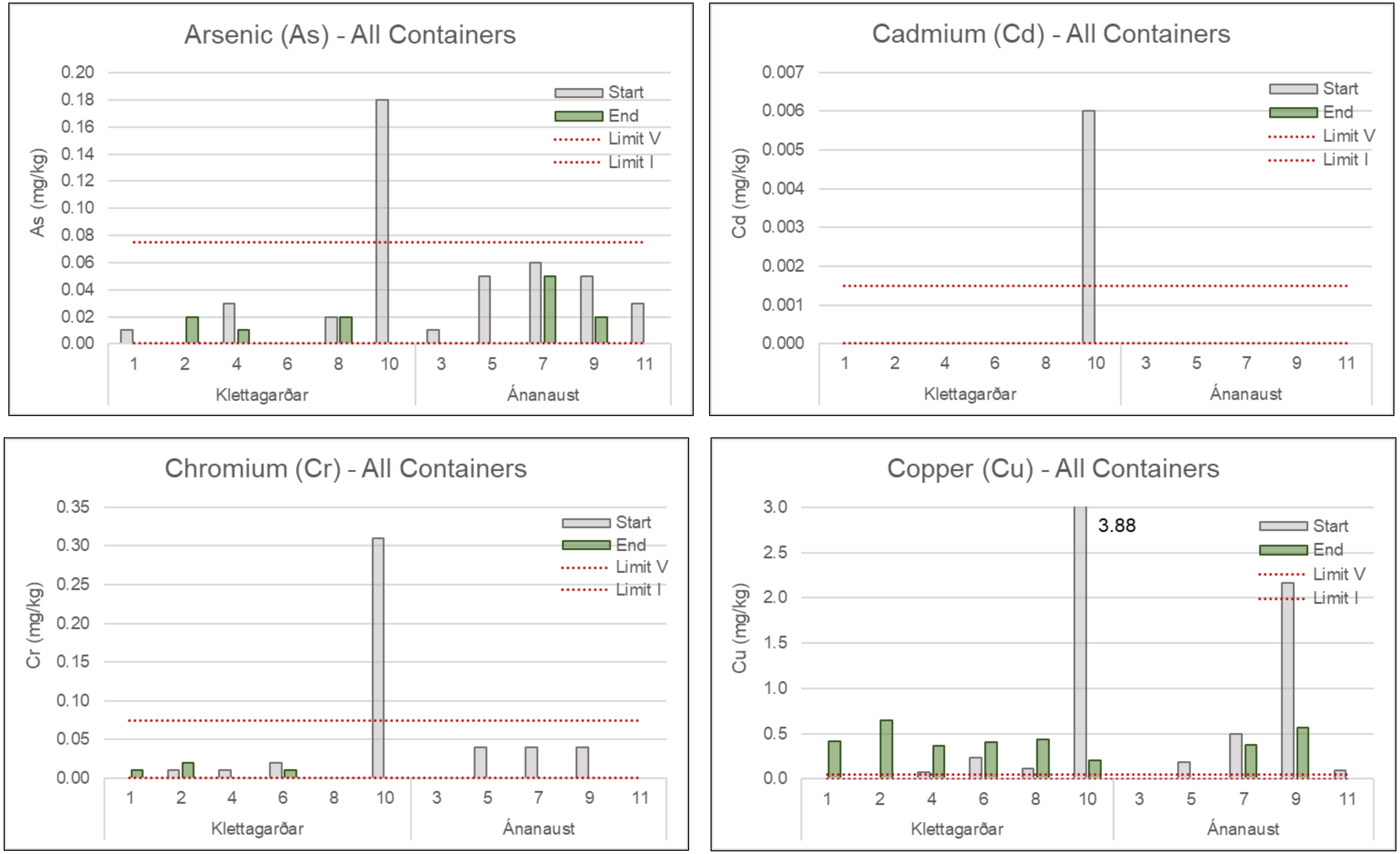

Figure 17. Concentration of heavy metals at the start and end of storage. The concentration for Cu is shown as number next to column for container 10.

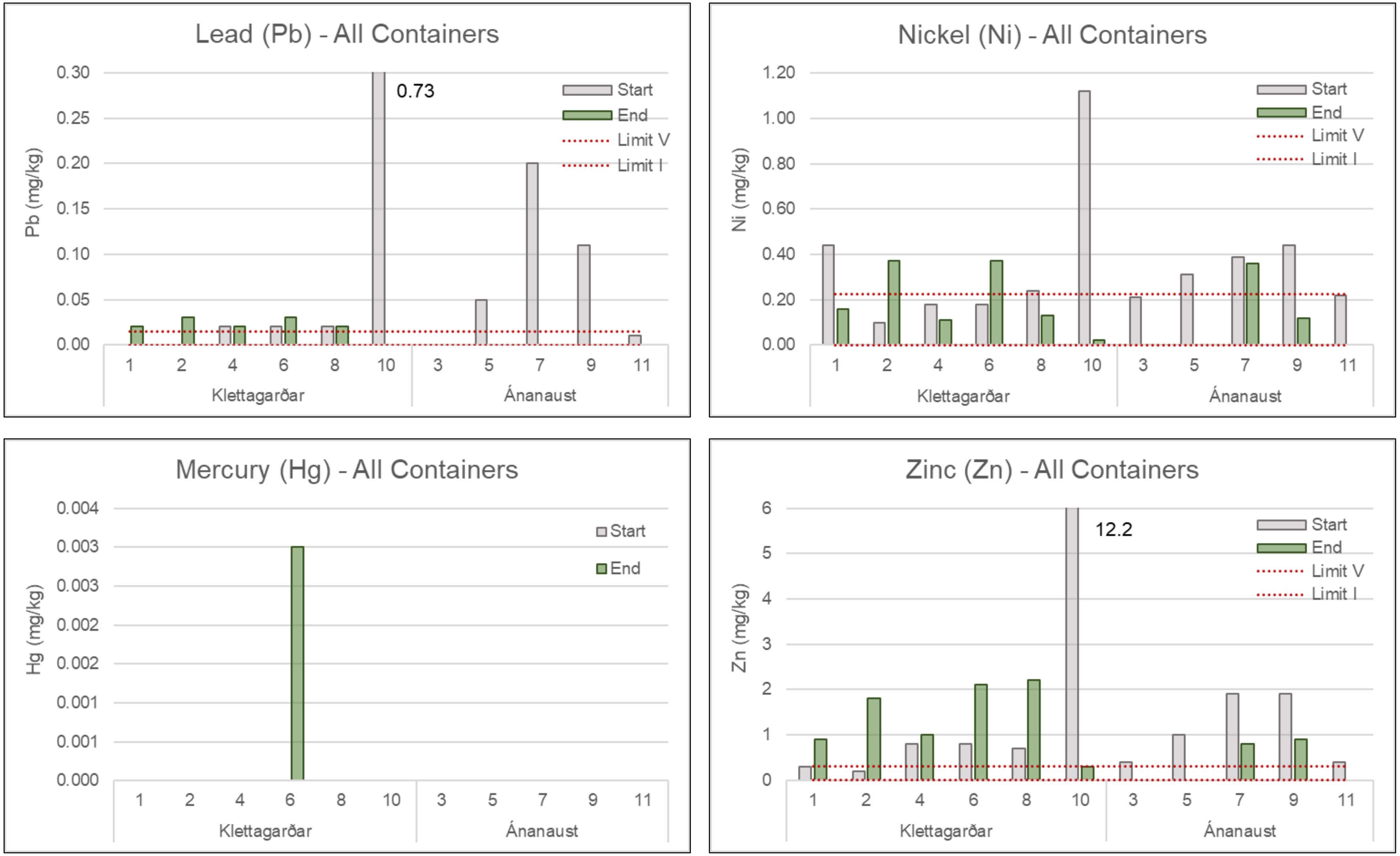

Figure 18. Concentration of heavy metals from all containers at the start and end of the storage. The concentration for Pb and Zn in container 10 plots outside of the scale, in that case value is shown as number next to column.

Table 8. Chemical analysis, results based on leaching (DIN EN ISO 17294-2 (E29): 2017-01 and DIN EN ISO 12846 (E12): 2012-08).

		Klettagarðar						**Ánanaust**				
		1	**2**	**4**	**6**	**8**	**10**	**3**	**5**	**7**	**9**	**11**
Arsenic (As) mg/kg	Start	0.01	<0.01	0.03	<0.01	0.02	0.18	0.01	0.05	0.06	0.05	0.03
	End	<0.01	0.02	0.01	<0.01	0.02	<0.01	<0.01	<0.01	0.05	0.02	<0.01
Lead (Pb) mg/kg	Start	<0.01	<0.01	0.02	0.02	0.02	0.73	<0.01	0.05	0.20	0.11	0.01
	End	0.02	0.03	0.02	0.03	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cadmium (Cd) mg/kg	Start	<0.003	<0.003	<0.003	<0.003	<0.003	0.006	<0.003	<0.003	<0.003	<0.003	<0.003
	End	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Chromium (Cr) mg/kg	Start	<0.01	0.01	0.01	0.02	<0.01	0.31	<0.01	0.04	0.04	0.04	<0.01
	End	0.01	0.02	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Copper (Cu) mg/kg	Start	<0.05	<0.05	0.07	0.23	0.11	3.88	<0.05	0.18	0.50	2.16	0.09
	End	0.42	0.65	0.36	0.41	0.44	0.2	<0.05	<0.05	0.37	0.57	<0.05
Nickel (Ni) mg/kg	Start	0.44	0.10	0.18	0.18	0.24	1.12	0.21	0.31	0.39	0.44	0.22
	End	0.16	0.37	0.11	0.37	0.13	0.02	<0.01	<0.01	0.36	0.12	<0.01
Mercury (Hg) mg/kg	Start	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
	End	<0.002	<0.002	<0.002	0.003	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Silver (Ag) mg/kg	Start	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
	End	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Zinc (Zn) mg/kg	Start	0.30	0.20	0.80	0.80	0.70	12.20	0.40	1.00	1.90	1.90	0.40
	End	0.90	1.80	1.00	2.10	2.2	0.3	<0.01	<0.01	0.80	0.9	<0.01

The total organic carbon (TOC) indicates the total amount of carbon from organic material present in a sample. TOC analyses were performed on sand samples as the containers were deployed and by the end of the experimental storage period (table 9 and figure 19).

Table 9. Results of chemical analysis, TOC and COD, from all containers. Values from Klettagarðar shown in blue and from Ánanaust in yellow.

		Klettagarðar						**Ánanaust**				
		1	**2**	**4**	**6**	**8**	**10**	**3**	**5**	**7**	**9**	**11**
TOC (mg/l)	Start	77	170	190	37	350	2,100	66	250	250	330	260
	End	37	50	30	30	58	23	1	2.5	53	110	3.8
COD (mg/l)	Start	115	353	410	123	1,020	6,650	162	682	820	906	147
	End	124	167	115	101	256	91	<15	<15	875	388	<15

The mean TOC value in Klettagarðar containers before screen renewal is around 165 mg/l and after weeks of storage the mean value is around 41 mg/l, thus 75% reduction. After screen renewal the TOC value increases significantly, in container 10 from Klettagarðar the TOC is 2100 mg/l, however after the experimental storage period values are significantly lower, 23 mg/l, below the mean value.

The mean TOC values from Ánanaust containers are around 231 mg/l and after weeks of storage the mean value is around 34 mg/l, thus an 85% reduction.

The TOC values indicate that the sand from the wastewater treatment plant in Ánanaust has significantly higher values of organic matter compared to Klettagarðar.

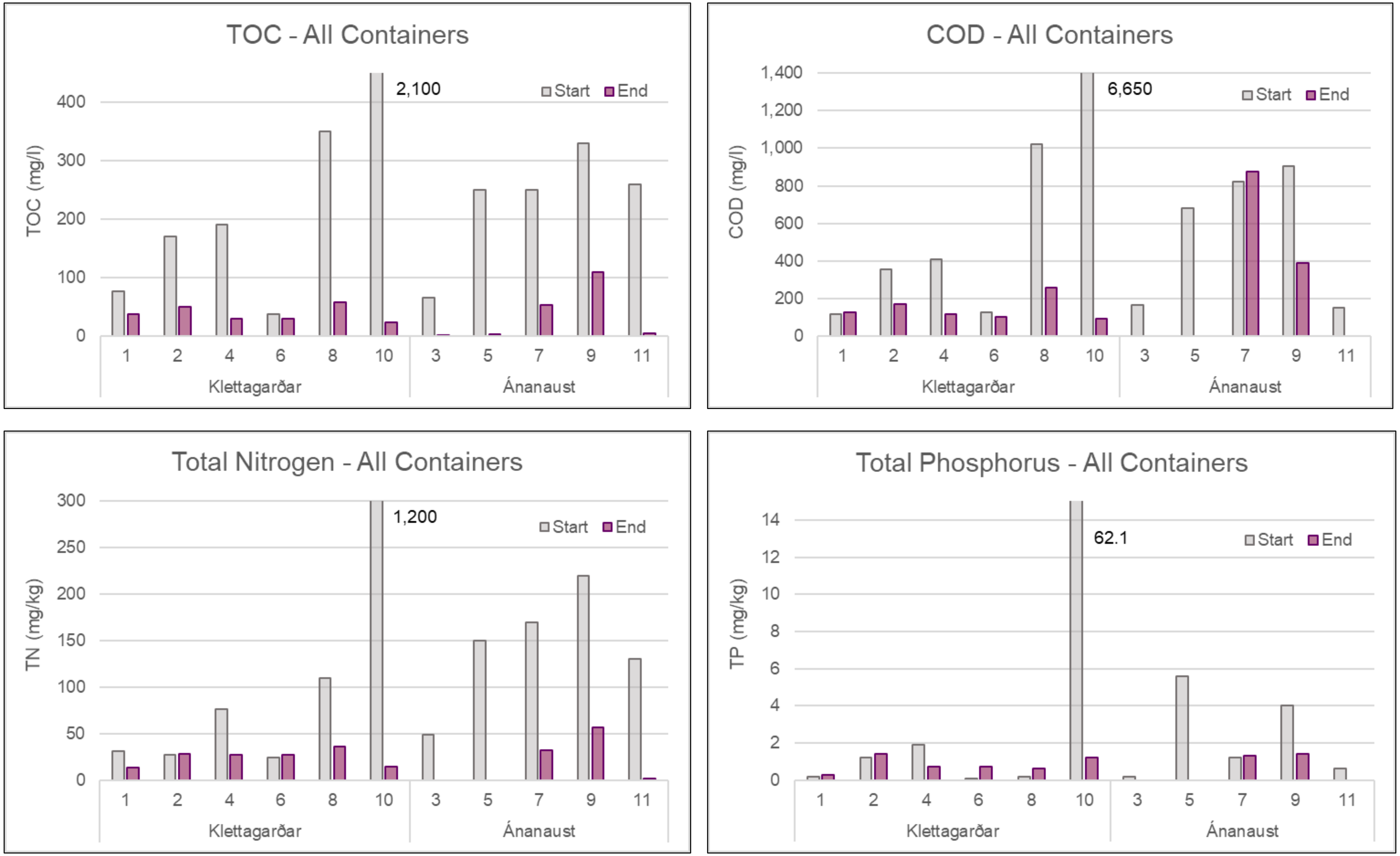

Figure 19. Concentration of organic matter, total nitrogen and phosphorus from all containers at the start and end of the storage. Values in the start for container 10 from Klettagarðar are noted next to the column since the scale is adjusted to better show the data.

The chemical oxygen demand (COD) indicates the amount of oxygen required for the oxidation of all organic substances in water. Thus, COD is an indirect measurement of the amount of organic matter in a sample. COD analyses were performed on sand samples as the containers were deployed and by the end of the experiments (table 9 and figure 19).

The mean COD value in Klettagarðar containers before screen renewal is around 250 mg/l and after weeks of storage the mean values are around 127 mg/l, thus 49% reduction. After changing the screens, the COD values increase significantly, in container 10 the COD is 6650 mg/l, however after the experimental storage period values are significantly lower, 91 mg/l.

The mean COD values from Ánanaust containers are on average higher than in Klettagarðar when deployed, around 543 mg/l. After weeks of storage the mean values are around 262 mg/l, thus 52 % reduction.

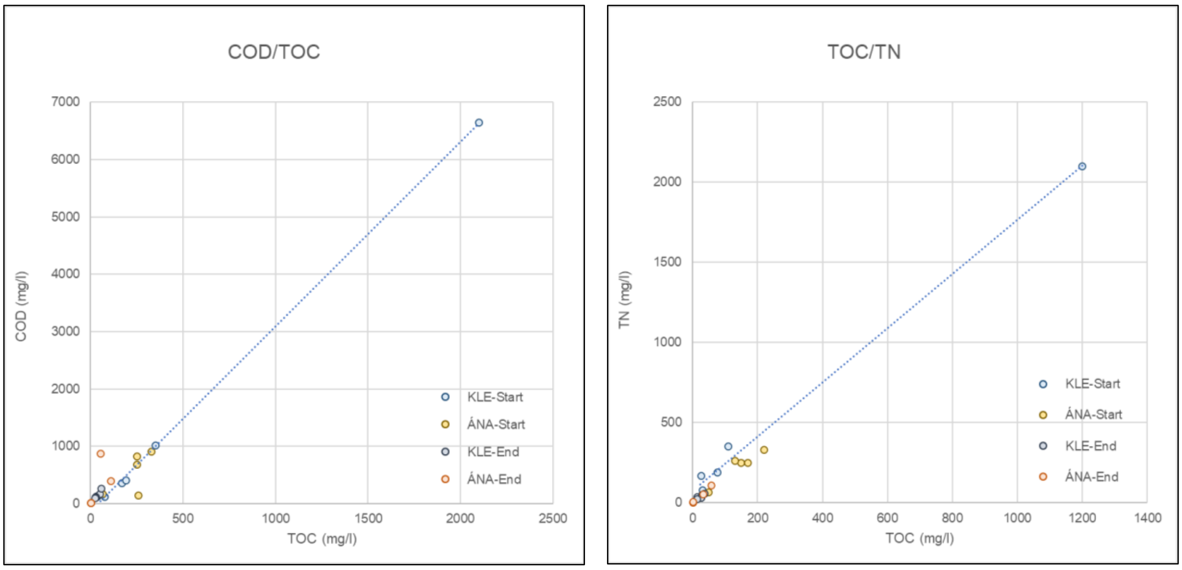

Figure 20. COD/TOC ratio decreases during storage, with less impact on oxygen concentration in the receiver. TOC/TN ratio decreases as well during storage.

The COD/TOC ratio is a measure of the average oxidation state of the carbon in a specific compound of waste sample (figure 20). The higher the COD/TOC ratio, the more impact the waste sample will have on the surface water oxygen concentration. The only sample that might have a high impact on the surrounding water oxygen concentration results is from container 10, although one should keep in mind that that sample is taken before storage.

Bacteria need Carbon as an energy source and Nitrogen is used for cell building. The lower the C:N ratio, the more rapidly nitrogen will be released into the soil for immediate use (Watson et al., 2002). The humidity in the sand and the C:N ratio can thus have an effect on the survival rate of different microbiota.

Table 10. Chemical results, lipophilic compounds, phosphorus, and various types of nitrogen compounds.

		Klettagarðar						Ánanaust				
		1	**2**	**4**	**6**	**8**	**10**	**3**	**5**	**7**	**9**	**11**
Low volatile lipophilic compoounds (mg/l)	Start	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	End	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Phosphorus (mg/l)	Start	0.2	1.2	1.9	0.1	0.2	62.1	0.2	5.6	1.2	4.0	0.6
	End	0.3	1.4	0.7	0.7	0.6	1.2	<0.1	<0.1	1.3	1.4	<0.1
Total Nitrogen bound (mg/l)	Start	31	27	76	24	110	1,200	49	150	170	220	130
	End	14	28	27	27	36	15	<1.0	<1.0	32	57	2.1
Nitrate (as NO3) (mg/l)	Start	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
	End	<1.0	<1.0	73	7.1	13	<1.0	<1.0	<1.0	120	190	<1.0
Nitrate nitrogen (N)(mg/l)	Start	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
	End	<0.25	<0.25	17	1.6	2.9	<0.25	<0.25	<0.25	26	43	<0.25
Nitrite (as NO2) (mg/l)	Start	<0.01	<0.01	<0.01	0.14	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01
	End	1.1	<0.01	1.1	13.0	0.81	<0.01	0.071	0.069	0.06	0.42	<0.01
Nitrite (as N) (mg/l)	Start	<0.003	<0.003	<0.003	0.043	<0.003	<0.003	<0.003	<0.003	<0.003	0.005	<0.003
	End	0.34	<0.003	0.35	4.0	0.25	<0.003	0.022	0.021	0.018	0.13	<0.003
Ammonium (mg/l)	Start	34	19	71	21	92	990	51	130	180	180	120
	End	11	34	10	20	34	17	0.34	0.39	3.2	15	2
Ammonium (NH4-N) (mg/l)	Start	26	15	55	16	71	770	40	100	140	140	91
	End	8.7	18	8.1	15	26	13	0.26	0.3	2.5	12	1.5

All values of low volatile lipophilic compounds are below detection limits (<10 mg/l) and will thus not be discussed in further detail in this assessment.

The total phosphorus in the sand from Klettagarðar increased during storage in container, 1, 2 and 6 of up to 600%. Only in container 4 did the value decrease by 63% (table 10 and figure 19). The amount of soluble phosphorus in soil is heavily affected by temperature and moisture conditions, which could be the reason for 63% lower values in container 4 since the sand in container 4 dehydrated the most during storage.

Wastewater discharge from treatment plants contains amounts of Nitrogen compounds originating from human waste, foods, certain soaps, cleaning detergents and discharges from industrial and commercial sources (table 10 and figure 19). When the nitrogen concentration is too high it can result in algae blooms that deplete oxygen needed by aquatic life. Some of the nitrogen compounds are deposited with the washed sand, therefore we measured all nitrogen-based pollutants such as ammonia, nitrate, nitrite, and organic nitrogen compounds.

Based on the chemical analysis we can see a biological process of nitrification in our data (table 10). Where nitrifiers convert nitrogen in the form of ammonia (NH3) into nitrite (NO2) and then nitrate (NO3-) under aerobic conditions. When the containers are deployed the values of ammonia are high and thus of nitrite and nitrate are low. On the controversy, after storage, the concentration of ammonia is low, but nitrite and nitrate are higher.

The total nitrogen values vary considerably between the containers, from 24 mg/l to 1200 mg/l on their start dates. The highest values are in container 10 where TOC and COD are high as well. After the experimental storage period the values decrease by 50-60% in two containers and increase by 4-13% in two containers.

5 Life cycle analysis

5.1 Goal and scope

In this assessment the aim was to perform a comparative attributional Life Cycle Assessment (LCA) to evaluate the environmental impacts and benefits associated with two distinct sand sourcing alternatives for construction projects: (i) sand sourced from a wastewater treatment plant and (ii) sand sourced from a quarry. Furthermore, to identify the most efficient process for sand utilization, several scenarios of sand utilization are considered which differ in transport and how the sand is stored. The study intends to provide scientifically robust insights into the environmental performance of these sand sources through cradle to grave, or from extraction to final use at a construction site.

5.1.1 Scenarios

The whole process is further divided into three different scenarios of storing the sand, and each one of them is further subdivided into two categories, A and B, based on the frequency of transport and the type of container used. Table 11 describes each of the scenarios.

Scenarios 1, 2 and 3 differ in terms of storage. In scenario 1, the sand from both Klettagarðar and Ánanaust is sent to a storage plan where it is stored in one large pile. In scenario 2, sand from Klettagarðar is stored in a specific pile and sand from Ánanaust is stored in another pile. The last scenario, following the initial ones, also sees the sand being transported to a designated storage plan. However, this scenario marks a notable shift in the storage methodology. In contrast to scenarios 1 and 2 where sand is accumulated in large piles, scenario 3 adopts the use of 12 containers for storage.

Each of scenarios 1,2 and 3 are then divided to subtype A and B. For subtype A, containers are sent to the storage site once they are filled and for subtype B, containers are sent to the storage plan once a month. It takes approximately 6,5 months to fill a 20 feet container at Klettagarðar and just over 13,5 months to fill up a 20 feet container at Ánanaust. In the B cases, a smaller container (10 foot long) is used and sent to the storage site once a month.

Based on data from previous years, it is enough to send one smaller container each month from the treatment plants. Klettagarðar produces 8.5 tons a month and Ánanaust 4 tons a month on average based on the data from previous years. However, Veitur is experiencing an increase in the washed sand from the wastewater treatment plants this year, with the amount of sand being higher than it has been for the past 7 years. The calculations were done using an approximate average amount from previous years before the increase.

Transport of “bacteria-free” sand from the storage site and to the construction site is constant across all scenarios.

Table 11. Description of utilization scenarios.

Scenarios	**Scenario sub-type**	**Transport from WW facilities**	**Storage management**	**Transport from storage site to construction site**
Scenario 1	A	Transport once a 20 feet container is filled (55 tonnes)	One pile	Transport every four months with 20 feet containers
	B	Transport every month		
Scenario 2	A	Transport once a 20 feet container is filled (55 tonnes)	Two piles	
	B	Transport every month		
Scenario 3	A	Transport once a 20 feet container is filled (55 tonnes)	Sand stored in containers	
	B	Transport every month		

Scenario 1, shown in figure 21, represents the concept of storing the washed sand as one large pile in the storage area. The sand from both treatment plants would be deposited in a large pile upon delivery to the storage, and then it would be necessary to wait at least 2 years for the sand to become ‘’bacteria-free’’.

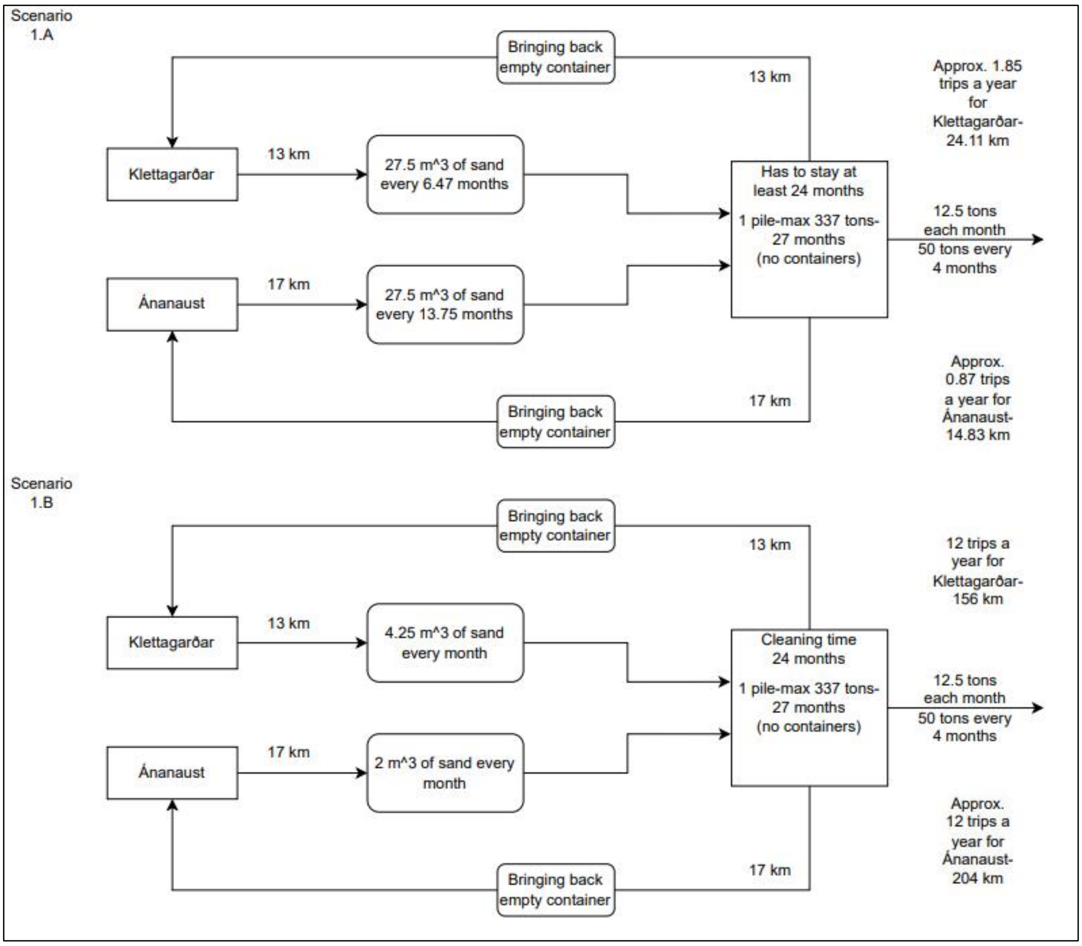

Figure 21. Flowchart of scenario 1.

In figure 22, scenario 2 is shown, where the sand is divided into two different piles based on its origin (Klettagarðar or Ánanaust), since the washed sand from Klettagarðar requires shorter processing time and is thus available earlier for utilization (12 months) than the washed sand from Ánanaust (24 months). This means that sand would be accessible earlier for utilization at the construction sites.

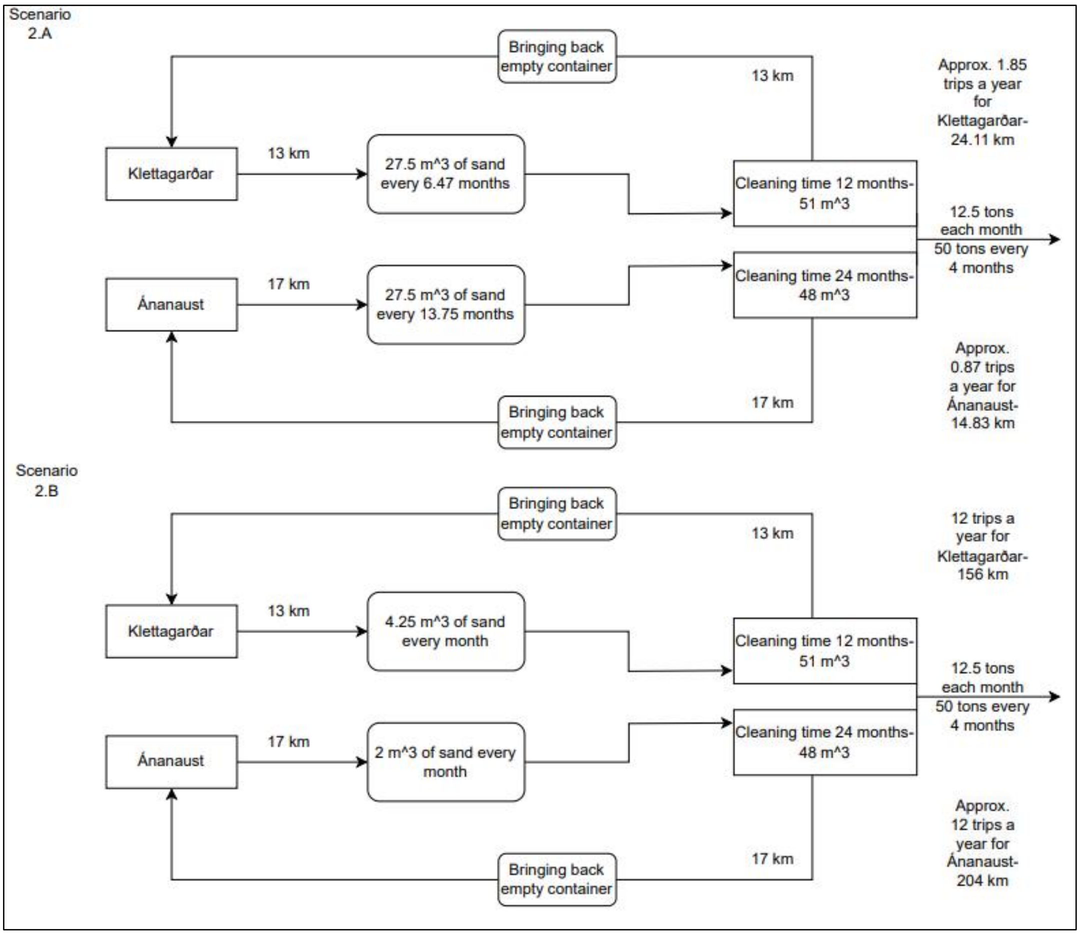

Figure 22. Flowchart of scenario 2.

Scenario 3 in figure 23 involves storing the sand in containers instead of a pile, so each ‘batch’ is going to have its own processing period. The containers used for storage in this scenario would be large containers (20 feet).

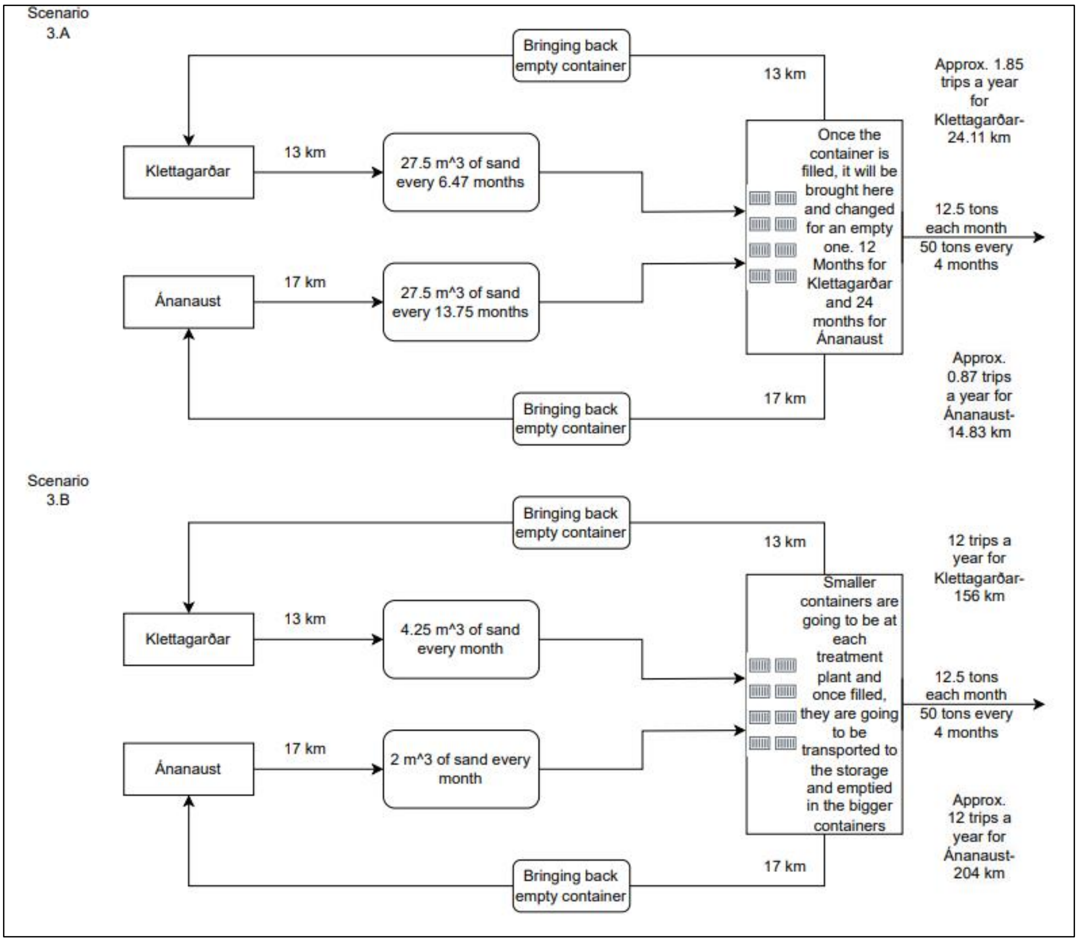

Figure 23. Flowchart of scenario 3.

5.1.2 Functional unit

The functional unit for this assessment is defined as 1 tonne of sand at a construction site, applied as filling material around wastewater pipes. This sand can either come from a wastewater treatment plant in Reykjavík or be bought from a sand factory that mines the sand in a quarry. As mentioned before, the sand properties do not meet the sand requirements for sand used as an insulation around electric cables, with both humidity and heat resistance being high. However, the requirements for sand use around the wastewater pipes as filling are less strict. Washed sand from the treatment plant falls within the criteria for use as filling, and therefore it was decided for the purposes of the LCA to compare it with the sand mined and purchased for use as filling around the wastewater pipes.

The functional unit of 1 tonne is chosen primarily because it can be scaled up or down based on needs, allowing the results to be applicable in future studies and projects.

5.1.3 System boundaries

The system boundary encompasses all additional processes associated with utilization. Since both utilization and non-utilization do include the washing of sand, the only additional process is that the sand is collected into a container and sent to a storage site. It will consider all direct and indirect environmental inputs and outputs associated with these processes. Table 12 shows which life cycle stages are considered and included in the system.

Table 12. Description of life cycle stages included (X = included, NI = not included). Note that stages are not included on the grounds that they are identical for both utilization scenarios and for non-utilization scenarios.

Production stage			Construction stage		Use stage					End of life stage**				
Raw material supply	Transport to factory	Manufacturing	Transport to site	Construction-installation	Use	Maintenance	Repair	Replacement	Refurbishment	Deconstruction / demolition	Transport	Waste processing	Disposal of waste	Reuse / recycling / recovery
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
X*	X	X	X	X	X	X	X	X	X	X	X	X	X	NI

*Raw material supply is only considered for quarrying. Not applicable to WW facilities since only added infrastructure is analyzed. **End of life stage only applied to sand from WW facilities in the "no utilization" scenario where sand is sent to a landfill site. This is due to no end-of-life processes being applied other than landfilling of sand within the 25-year timeframe.

The system boundary is further described in the flowchart represented in figure 24. In scenarios where sand is obtained from a wastewater treatment facility, this encompasses all the additional infrastructure needed for transporting and storing the sand prior to its use. The base case, however, will assess the existing practice where sand from the wastewater treatment facility is disposed of in landfills, and construction sand is sourced from a sand quarry.

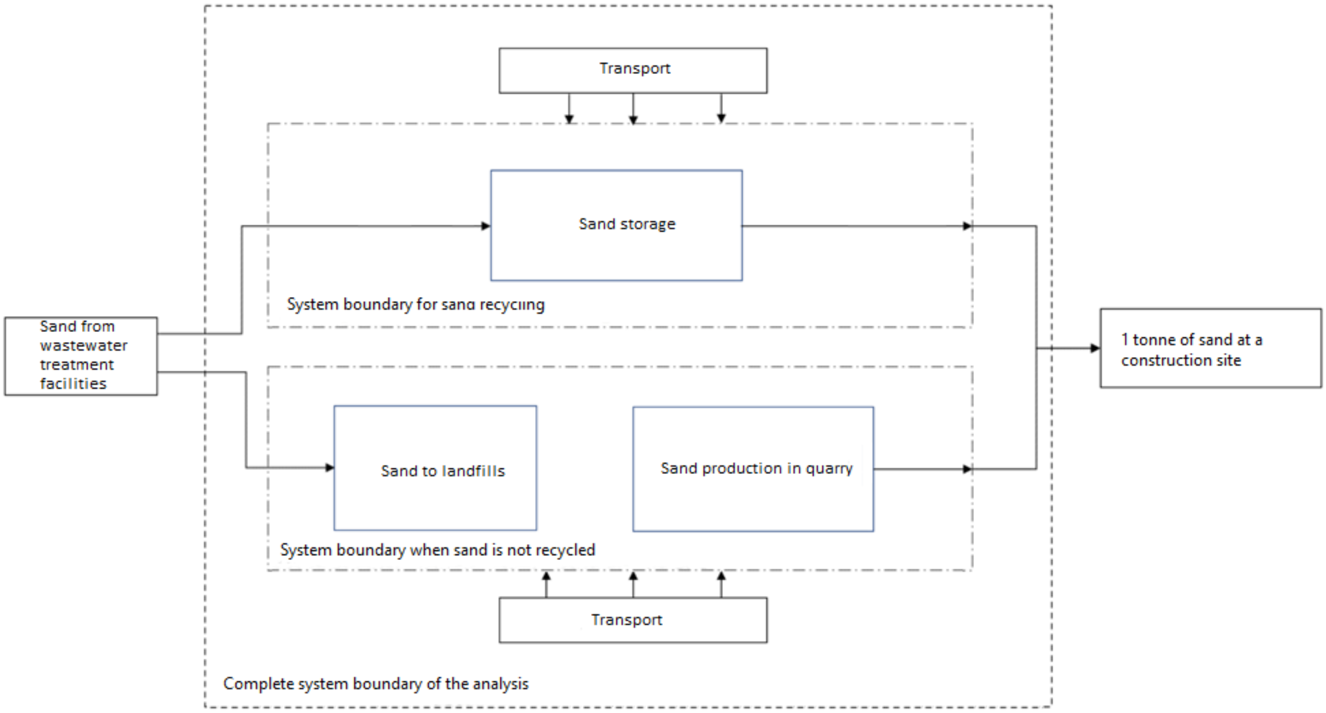

Figure 24. System boundary of sand utilization and of a no recycling scenario.

5.1.4 Software, databases and impact categories

All impact categories from ReCiPe Midpoint life cycle impact assessment method were calculated. Data on the environmental impacts of each process is obtained from the software openLCA. The Ecoinvent database was used to model all processes in the system. The included impact categories were the following:

- Climate Change Potential: Contribution to climate change due to greenhouse gasses emitted by the project, such as carbon dioxide, methane and nitrous oxide are considered. It is a shared interest of countries all over the world to reduce the emissions produced and eventually become carbon neutral to stop and mitigate warming of the planet, decreasing the risk of possible damage caused by natural disasters.
- Fossil Depletion: In this impact category evaluates the total depletion of non-renewable fossil fuels such as natural gas, coal, and oil. In some cases, EROEI (Energy return on energy invested) is also described.
- Freshwater Ecotoxicity: This category assesses the danger posed to water system. This includes the concentration and persistence of toxic substances that are released to the water bodies. This can affect species living in them by disrupting their food chains, reproductive system and affecting biodiversity in many ways.
- Freshwater Eutrophication: Not only are harmful chemicals released into the water during daily processes, but also a significant number of nutrients end up in the water bodies. Nutrients such as Phosphorus and Nitrogen can cause an increase of plant and algae in the water bodies, eventually leading to oxygen depletion in the water.
- Human Toxicity: Both direct (e.g., skin to material contact) and indirect (e.g., air, water, soil) exposures of toxic substances to the human body can cause unwanted health effects. These effects can be both chronic and acute.
- Ionizing Radiation: Health and the environment are at risk when exposed to ionizing radiation. This can occur due to human sources of radiation, such as medical applications, nuclear power plants or radiating/radioactive waste and natural sources like radon gas.
- Marine Ecotoxicity: Marine Ecotoxicity is like freshwater ecotoxicity, except it is adjusted and shifts the focus on marine ecosystems. It includes the impact on organisms present in the water and their food chain.
- Marine Eutrophication: Similar to freshwater eutrophication, except it evaluates the impact on marine ecosystem. Nutrients released into the marine environments can cause algae blooms, reducing the oxygen in the water and disrupting the original ecosystem.
- Metal Depletion: Focuses on the depletion of metal resources caused by usage and extraction. The process includes many factors like scarcity, rate of extracting metals and potential for recycle/reuse.
- Natural Land Transformation: Natural lands/habitats such as forests, wetlands, and rivers are usually disrupted and transformed into agricultural or urban areas.
- Ozone Depletion: Assesses the potential of chemicals produced and released during the processes to deplete ozone layer in the atmosphere, which serves as a barrier that protects Earth from ultraviolet radiation.
- Particulate Matter Formation: Measures the total emissions of particulate matter and their potential impact on human health, air, soil, water, and environment.
- Photochemical Oxidant Formation: Photochemical oxidants, like ground-level ozone, can be formed due to emissions of volatile organic compounds or nitrogen oxides. These oxidants are significant contributors to smog and are harmful to living organisms.

- Terrestrial Acidification: Acidification can lead to soil degradation, loss of biodiversity, and damage to life in water bodies. To quantify the protentional problem and danger, acidifying emissions like sulfur dioxide and nitrogen oxides on soil, water and ecosystems are measured.
- Terrestrial Ecotoxicity: Evaluates the potentially harmful and toxic effect of chemical substances that were released into the soil during the processes. It can affect the fertility of the soil, accumulation of toxic substances in the food chain, and disrupt biodiversity in the soil.
- Urban Land Occupation: Environmental impact of land use for urban development is assessed in this category. The assessment includes habitat destruction, changes in hydrology and ecosystems in the area.
- Water Depletion: Measures the amount of freshwater used and depleted, and the manner in which the water was obtained and distributed until it was used.

5.2 Life cycle inventory

This section outlines the inventory for the analysis, which includes all specific processes for sand recycling, waste management, and sand production in a quarry. It covers transportation, the production of necessary equipment, containers or machinery for recycling or sand production, and the construction of a sand storage plan. The key processes in the LCA inventory are presented in table 13.

Table 13. LCA inventory overview and inclusion in utilization scenarios and no utilization scenario.

Processes	Included	
	Sand utilization	No utilization
Containers	Yes	Yes
Sand quarry	No	Yes
Sand transportation	Yes	Yes
Excavator usage	Yes	Yes
Concrete storage area	Yes	No
Sand to waste	No	Yes

5.2.1 Containers

Each scenario requires different types and quantities of containers for transport or storage. For transport in the 'B' scenario versions, a small 20-feet container is used, while a larger 40-feet container is used in the 'A' scenario versions and for storage in the third scenario. It is assumed that an old container is recycled to manufacture a new one during the production process.

5.2.2 Sand from quarry

Sand production accounts for the environmental impact of standard quarry operations.

5.2.3 Transportation

Transportation is modelled using relevant processes from Ecoinvent, with three different vehicle size categories based on the quantity of sand being carried. These are categorized into small-, medium- and large sized lorries. Table 14 presents a description and the relevant Ecoinvent process used to model these transportation modes. Transportation processes are modelled using ton-kilometres. This requires that all transport routes across all scenarios are modelled for both distance and weight being carried on route. All vehicles are assumed to meet the EURO 4 emission standard.

Table 14. Transport modes modelled.

Type of transport	Description	Ecoinvent process
Small lorry	Lorry designed to carry a load between 3.5-7.5 metric ton.	lorry 3.5-7.5 metric ton, EURO4
Medium lorry	Lorry designed to carry a load between 7.5-16 metric ton.	lorry 7.5-16 metric ton, EURO4
Large lorry	Lorry designed to carry metric ton >32 metric tons.	lorry, >32 metric ton, EURO4

For distance calculations for transport, Reynisvatnsheiði is suggested in this assessment as the designated area for sand storage. This does not mean that Veitur currently intend to use the site for this purpose, the site was simply chosen for the purposes of this analysis. The construction site's location is estimated based on the center of gravity from Veitur’s past construction sites in Reykjavík (figure 25). Figure 25 shows key locations for the transport model, including wastewater facilities (purple boxes), the assumed sand storage area (black box), the projected construction site (blue box, based on the center of gravity of all projects), and the location for landfilling of sand (orange box).

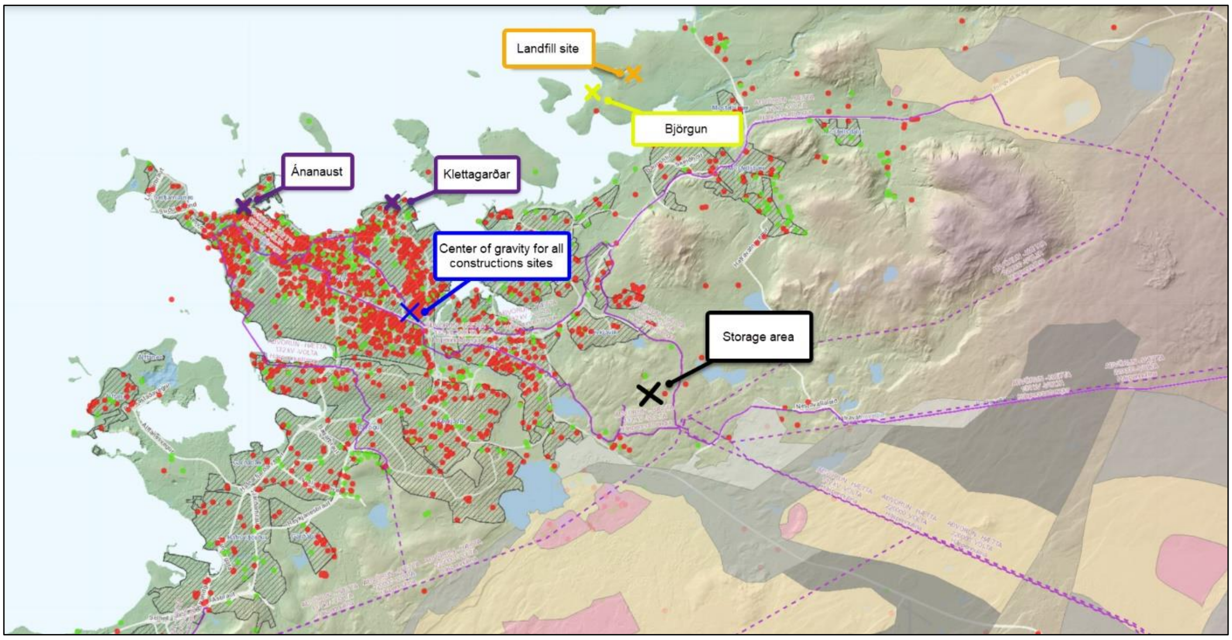

Figure 25. Reference locations used to model transport distances.

The estimated transport distances for all scenarios are based on the following modelled routes. To calculate the distance that the sand travels, various routes have been considered. These routes are essential for understanding the transportation impact in each scenario:

1. From wastewater facilities to storage site
   a. 13 km distance from Klettagarðar
   b. 17 km distance from Ánanaust
2. From storage site to construction site, 11.1 km distance
3. From quarry to Álfsnesvík, to construction site, 54 km distance
4. From wastewater facilities to landfill sites
   a. 21 km distance from Klettagarðar
   b. 23 km distance from Ánanaust

Tables 15, 16, and 17 feature color-coding for ease of interpretation: red indicates the highest values, yellow denotes medium values, and green signifies the lowest values. Distances for each route under various scenarios are depicted in table 15.

Table 15. Distance of each route.

Transport (routes, km)	1.A	1B	2A	2B	3A	3B	No utilization
Transport from Klettagarðar to storage	13.00	13.00	13.00	13.00	13.00	13.00	0.00
Trip back	13.00	13.00	13.00	13.00	13.00	13.00	0.00
Transport from Ánanaust to storage	17.00	17.00	17.00	17.00	17.00	17.00	0.00
Trip back	17.00	17.00	17.00	17.00	17.00	17.00	0.00
Transport from storage to construction	11.10	11.10	11.10	11.10	11.10	11.10	0.00
Trip back	11.10	11.10	11.10	11.10	11.10	11.10	0.00
Transport from quarry to Björgun and to construction	0.00	0.00	0.00	0.00	0.00	0.00	54.00
Trip back	0.00	0.00	0.00	0.00	0.00	0.00	54.00
Transport from Klettagarðar to waste	0.00	0.00	0.00	0.00	0.00	0.00	21.00
Trip back	0.00	0.00	0.00	0.00	0.00	0.00	21.00
Transport from Ánanaust to waste	0.00	0.00	0.00	0.00	0.00	0.00	23.00
Trip back	0.00	0.00	0.00	0.00	0.00	0.00	23.00

Reflecting the scenarios, table 16 details the number of annual trips per route, calculated based on the lorry size and total sand transported during the study's timeframe.

Table 16. Number of trips a year.

Transport (routes)	1.A	1B	2A	2B	3A	3B	No utilization
Transport from Klettagarðar to storage	1.85	12.00	1.85	12.00	1.85	12.00	0.00
Trip back	1.85	12.00	1.85	12.00	1.85	12.00	0.00
Transport from Ánanaust to storage	0.87	12.00	0.87	12.00	0.87	12.00	0.00
Trip back	0.87	12.00	0.87	12.00	0.87	12.00	0.00
Transport from storage to construction	3.00	3.00	3.00	3.00	3.00	3.00	0.00
Trip back	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transport from quarry to Björgun and to construction	0.00	0.00	0.00	0.00	0.00	0.00	86.40
Trip back	0.00	0.00	0.00	0.00	0.00	0.00	86.40
Transport from Klettagarðar to waste	0.00	0.00	0.00	0.00	0.00	0.00	24.00
Trip back	0.00	0.00	0.00	0.00	0.00	0.00	24.00
Transport from Ánanaust to waste	0.00	0.00	0.00	0.00	0.00	0.00	12.00
Trip back	0.00	0.00	0.00	0.00	0.00	0.00	12.00

In table 17, the weight transported each trip for every route is shown, inclusive of the container's weight.

Table 17. Transported weight per trip.

Transport (weight, tonnes)	1.A	1B	2A	2B	3A	3B	No utilization
Transport from Klettagarðar to storage	57.30	10.80	57.30	10.80	57.30	10.80	0.00
Trip back	2.30	2.30	2.30	2.30	2.30	2.30	0.00
Transport from Ánanaus to storage	57.30	5.00	57.30	5.00	57.30	5.00	0.00
Trip back	2.30	1.00	2.30	1.00	2.30	1.00	0.00
Transport from storage to construction	52.30	52.30	52.30	52.30	52.30	52.30	0.00
Trip back	2.30	2.30	2.30	2.30	2.30	2.30	0.00
Transport from quarry to Björgun and to construction	0.00	0.00	0.00	0.00	0.00	0.00	52.30
Trip back	0.00	0.00	0.00	0.00	0.00	0.00	2.30
Transport from Klettagarðar to waste	0.00	0.00	0.00	0.00	0.00	0.00	10.80
Trip back	0.00	0.00	0.00	0.00	0.00	0.00	2.30
Transport from Ánanaust to waste	0.00	0.00	0.00	0.00	0.00	0.00	5.00
Trip back	0.00	0.00	0.00	0.00	0.00	0.00	1.00

In table 18, the ton-kilometers for each trip are quantified. This measure provides insight into the environmental impact associated with the transport distances and loads for various routes considered in the LCA study.

Table 18. Ton-kilometers travelled annually for each route. Transport modes are color-coded, where red = small lorry, yellow = medium sized lorry, green = large lorry.

Transport (ton*km per year)	1.A	1B	2A	2B	3A	3B	No utilization
Transport from Klettagarðar to storage	1,382	1,685	1,382	1,685	1,382	1,685	-
Transport back	55	359	55	359	55	359	-
Transport from Ánanaust to storage	850	1,020	850	1,020	850	1,020	-
Transport back	34	204	34	204	34	204	-
Transport from storage to construction	1,735	1,735	1,735	1,735	1,735	1,735	-
trip back	-	-	-	-	-	-	-
Transport from quarry to Björgun and to construction	-	-	-	-	-	-	267,339
Transport back	-	-	-	-	-	-	10,731
Transport from Klettagarðar to waste	-	-	-	-	-	-	5,443
Transport back	-	-	-	-	-	-	1,159
Transport from Ánanaust to waste	-	-	-	-	-	-	1,380
Transport back	-	-	-	-	-	-	276

5.2.4 Excavator usage

For sand to be delivered to a construction site from a storage area, an excavator is needed. Excavator is not needed for transport of the sand from a treatment plant to a storage area since the trucks can lift one side of the container to fully empty it.

5.2.5 Storage site

For the storage of sand, a new storage area must be built. The assumed location for storage is to the east of Reykjavík, called Reynisvatnsheiði. This does not mean that Veitur currently intend to construct such facilities, these assumptions are solely for the purposes of the analysis. As shown in figure 26, the area already has a road for a better access. To prevent possible contamination of the ground under the storage, it is necessary for the storage area to be paved with concrete with proper draining, both for better prevention of contamination and better/easier access and manipulation with the sand. The storage site was therefore modelled by estimating the amount of concrete used to construct the storage site.

Figure 26. Storage facility at Reynisvatnsheiði.

Since there are 3 scenarios and each of them is storing the sand in a different way. A different paved area is needed. The calculations were done with the help of Verkís.

5.3 Impact assessment and interpretation

The impact assessment results are presented in this section and analyzed. Section 5.3.1 presents impact assessment results, section 5.3.2 presents a hot-spot analysis, where critical processes are discussed, and section 5.3.3 discusses the sensitivity of the model.

5.3.1 Impact assessment results

The impact assessment for this study is conducted across all scenarios to determine which methods of storing and transporting sand have the least impact. Table 19 shows the impact per tonne of sand at the construction site after the timeframe of 25 years. Each scenario is color-coded for all impact categories where dark green marks the best scenario, and dark red marks the worst scenario. In general, scenario 3 came out worst, however, the “no-utilization” scenario had by far the highest impacts in human toxicity and urban land occupation.

Table 19. Impacts per tonne sand, highlighting the best (green) scenarios to the worst (red).

Impact categories	Unit per tonne sand	1.A	1B	2A	2B	3A	3B	No utilization
agricultural land occupation	m2*a	1.3.E+00	7.7.E-01	1.4.E+00	7.9.E-01	6.3.E+00	5.7.E+00	3.8.E-01
climate change	kg CO2-Eq	1.7.E+01	2.1.E+01	2.0.E+01	2.3.E+01	5.3.E+01	5.6.E+01	2.1.E+01
fossil depletion	kg oil-Eq	4.0.E+00	5.4.E+00	4.2.E+00	5.6.E+00	1.3.E+01	1.4.E+01	9.4.E+00
freshwater ecotoxicity	kg 1,4-DCB-Eq	3.1.E+00	2.2.E+00	3.1.E+00	2.2.E+00	1.5.E+01	1.4.E+01	4.5.E+00
freshwater eutrophication	kg P-Eq	6.5.E-03	5.2.E-03	6.7.E-03	5.4.E-03	2.9.E-02	2.7.E-02	5.7.E-03
human toxicity	kg 1,4-DCB-Eq	1.3.E+01	1.0.E+01	1.3.E+01	1.1.E+01	5.9.E+01	5.6.E+01	2.0.E+02
ionising radiation	kg U235-Eq	1.0.E+00	1.3.E+00	1.1.E+00	1.3.E+00	3.7.E+00	3.9.E+00	2.2.E+00
marine ecotoxicity	kg 1,4-DCB-Eq	2.7.E+00	1.9.E+00	2.7.E+00	1.9.E+00	1.3.E+01	1.2.E+01	4.2.E+00
marine eutrophication	kg N-Eq	2.0.E-02	2.5.E-02	2.1.E-02	2.7.E-02	5.8.E-02	6.4.E-02	1.6.E-02
metal depletion	kg Fe-Eq	6.5.E+00	4.8.E+00	6.6.E+00	4.8.E+00	3.2.E+01	3.0.E+01	1.7.E+00
natural land transformation	m2	3.2.E-03	4.9.E-03	3.5.E-03	5.1.E-03	8.4.E-03	1.0.E-02	-5.8.E-02
ozone depletion	kg CFC-11-Eq	1.3.E-06	2.1.E-06	1.4.E-06	2.2.E-06	3.4.E-06	4.2.E-06	4.2.E-06
particulate matter formation	kg PM10-Eq	4.1.E-02	4.2.E-02	4.4.E-02	4.4.E-02	1.5.E-01	1.5.E-01	6.5.E-02
photochemical oxidant formation	kg NMVOC	6.3.E-02	8.0.E-02	6.8.E-02	8.4.E-02	1.9.E-01	2.1.E-01	1.6.E-01
terrestrial acidification	kg SO2-Eq	6.7.E-02	7.4.E-02	7.2.E-02	7.9.E-02	2.3.E-01	2.4.E-01	1.2.E-01
terrestrial ecotoxicity	kg 1,4-DCB-Eq	3.0.E-03	3.6.E-03	3.1.E-03	3.7.E-03	8.5.E-03	9.1.E-03	4.1.E-03
urban land occupation	m2*a	4.7.E-01	5.5.E-01	4.9.E-01	5.7.E-01	1.1.E+00	1.2.E+00	4.6.E+00
water depletion	m3	6.9.E-02	5.6.E-02	7.3.E-02	6.0.E-02	2.9.E-01	2.8.E-01	-3.4.E+01

5.3.2 Hot spot analysis

In this section, a hot spot analysis is conducted and discussed for all scenarios previously outlined in chapter 5.1.1. Each scenario represents a different method of storing the sand, while 'A' and 'B' denote the frequency of transport. Three impact categories, over the timeframe of 25 years, are then analyzed specifically with climate change being analyzed first, where scenarios 1A and 2A had the lowest impacts and scenarios 3A and 3B had the highest impacts. Then, human toxicity is discussed, where scenarios 1B and 2B had the lowest impacts and the “no utilization” scenario had the highest impact. Lastly, water depletion is discussed where the “no utilization” scenario interestingly has a negative, and the lowest impact. In this study, 'negative impacts' in the water depletion category are actually indicative of a positive environmental outcome. Specifically, a negative value here signifies that the process contributes to water replenishment, thereby reducing overall water depletion and providing environmental benefits.

Hot spots are shown across all scenarios in figure 27 to figure 33. Impacts from production of containers was the most contributing factor in all utilization scenarios for agricultural land transformation, fossil depletion, freshwater ecotoxicity- and eutrophication, human toxicity, marine ecotoxicity, metal depletion, and water depletion. Transport contributes proportionally more in B scenarios compared to A since smaller lorries were used. This is due to larger lorries being more efficient per ton-kilometer of sand transported. In scenarios 1B and 2B, transport has a very high contribution to the impacts of the overall model. Especially fossil depletion, ionizing radiation, marine eutrophication, natural land transformation, ozone depletion, terrestrial ecotoxicity and urban land transportation. Transport only accounted for more than 50% in urban land transformation for scenarios 1A and 2A. In scenarios 3A and 3B, containers had by far the highest impact due to a large number of containers being used to store sand at the storage site. For the no utilization scenario, landfills had the highest overall contribution in all impact categories except for marine eutrophication, metal depletion and terrestrial ecotoxicity.

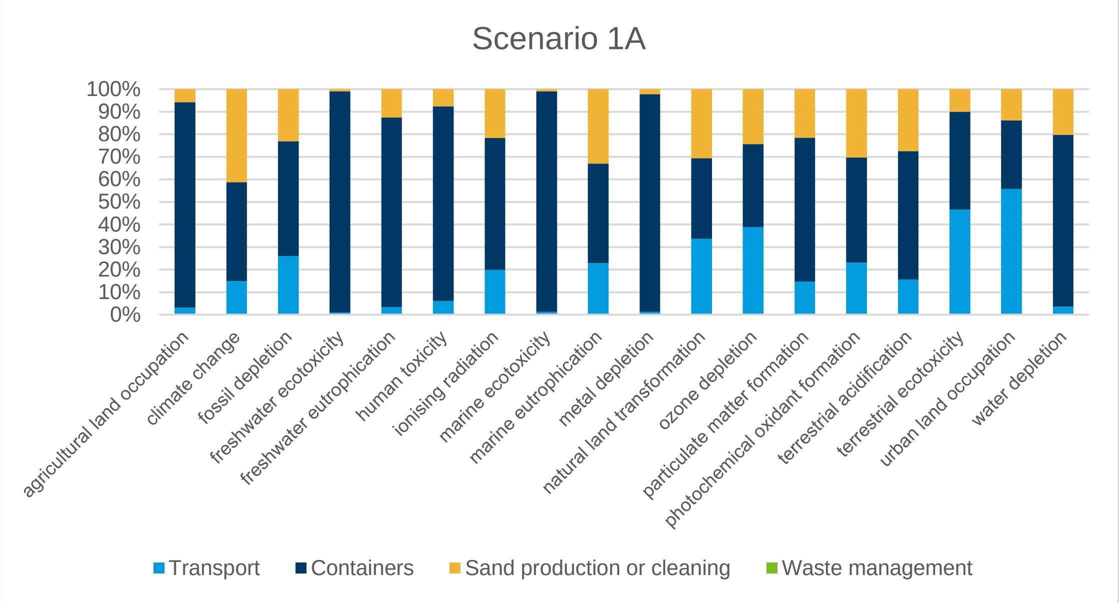

Figure 27. Hot spot results for scenario 1A.

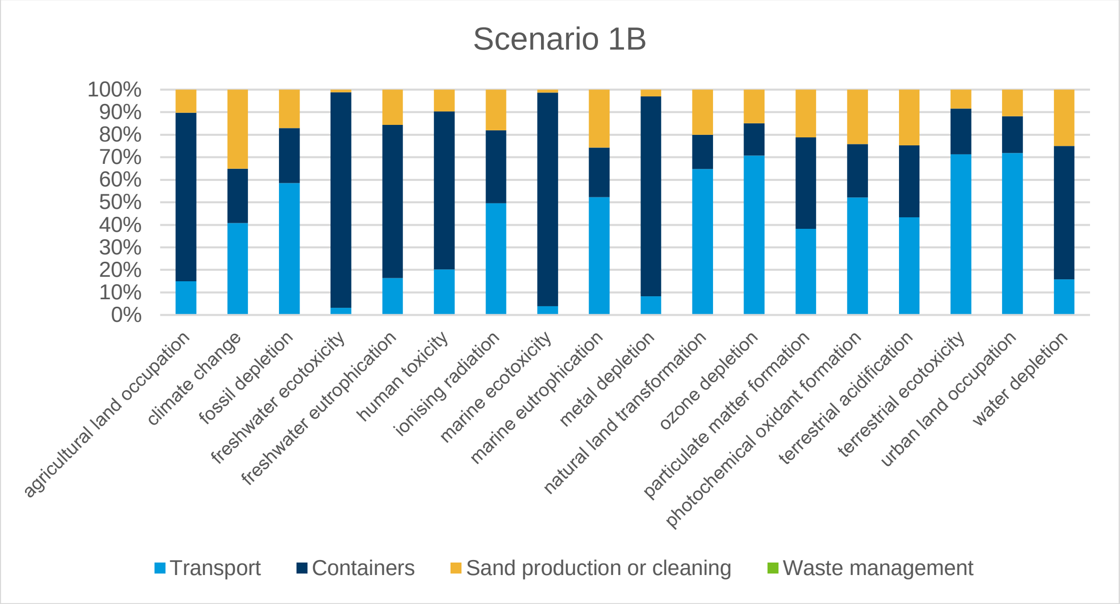

Figure 28. Hot spot results for scenario 1B.

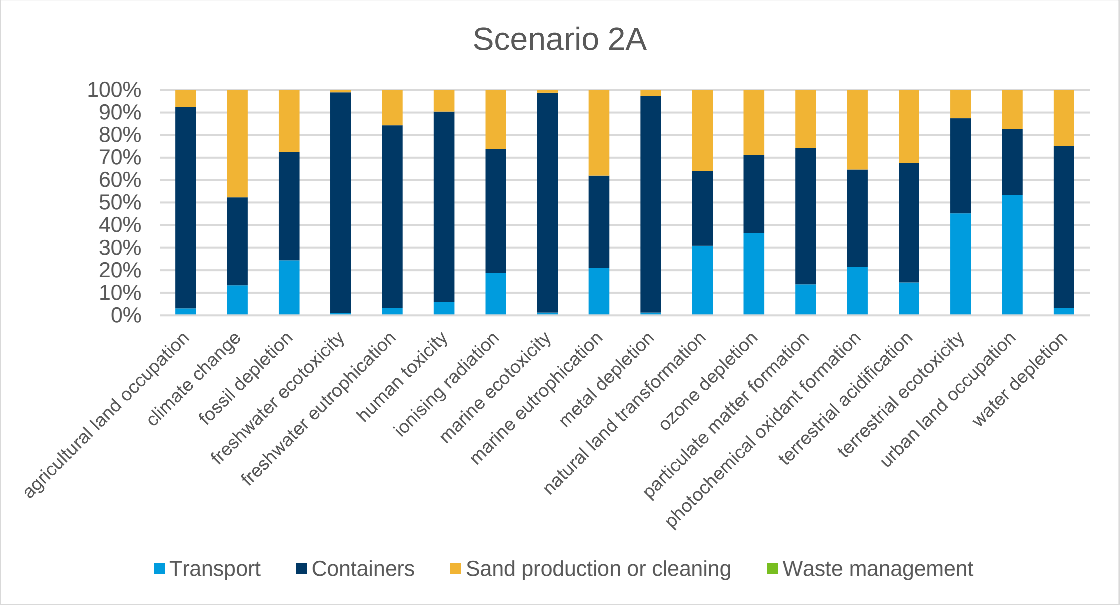

Figure 29. Hot spot results for scenario 2A.

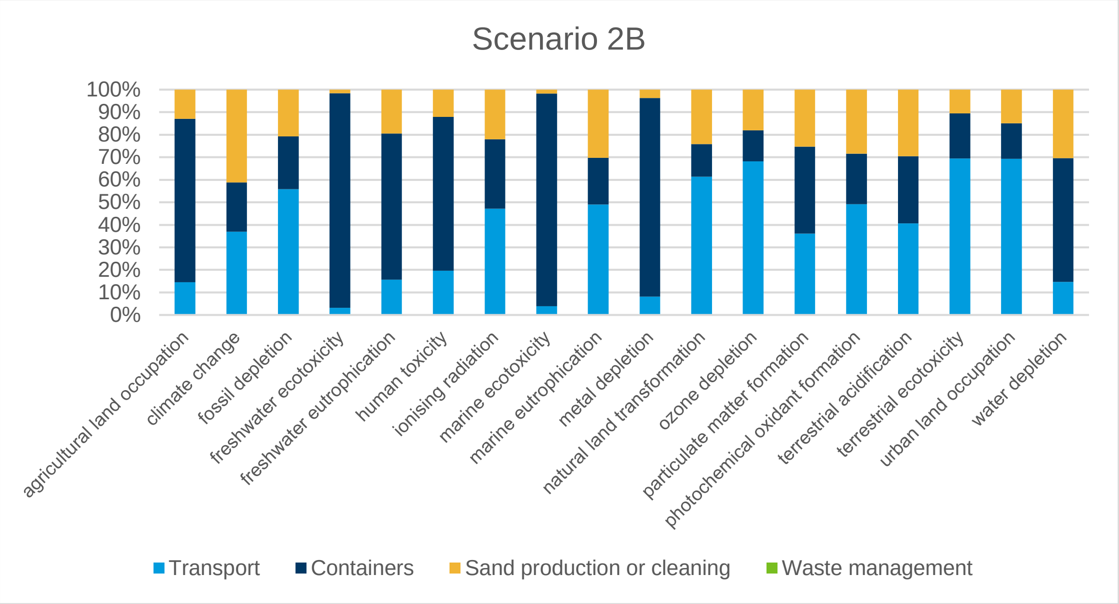

Figure 30. Hot spot results for scenario 2B.

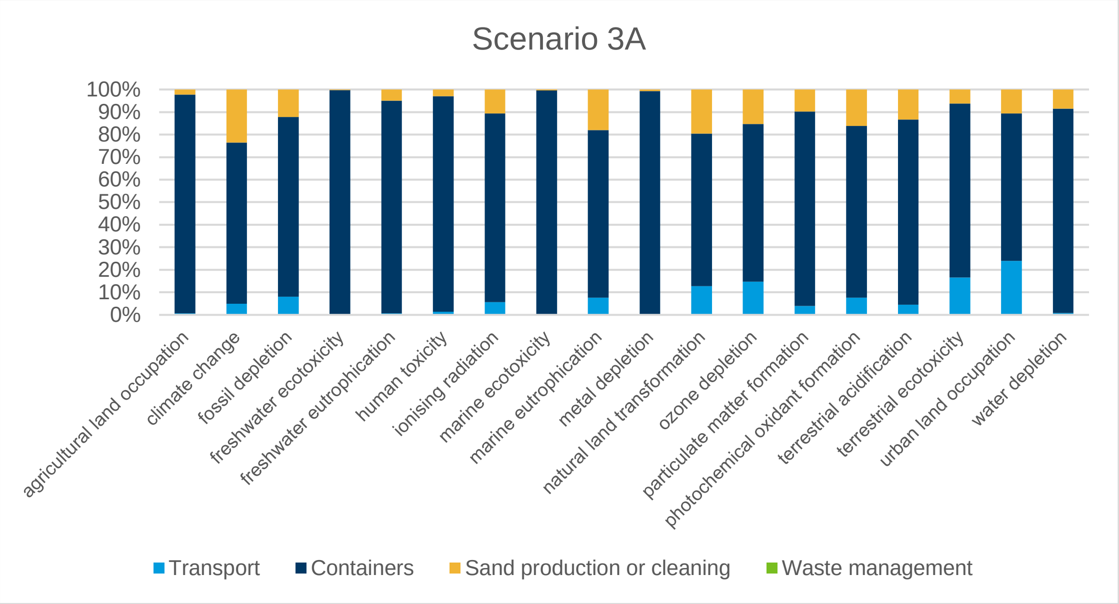

Figure 31. Hot spot results for scenario 3A.

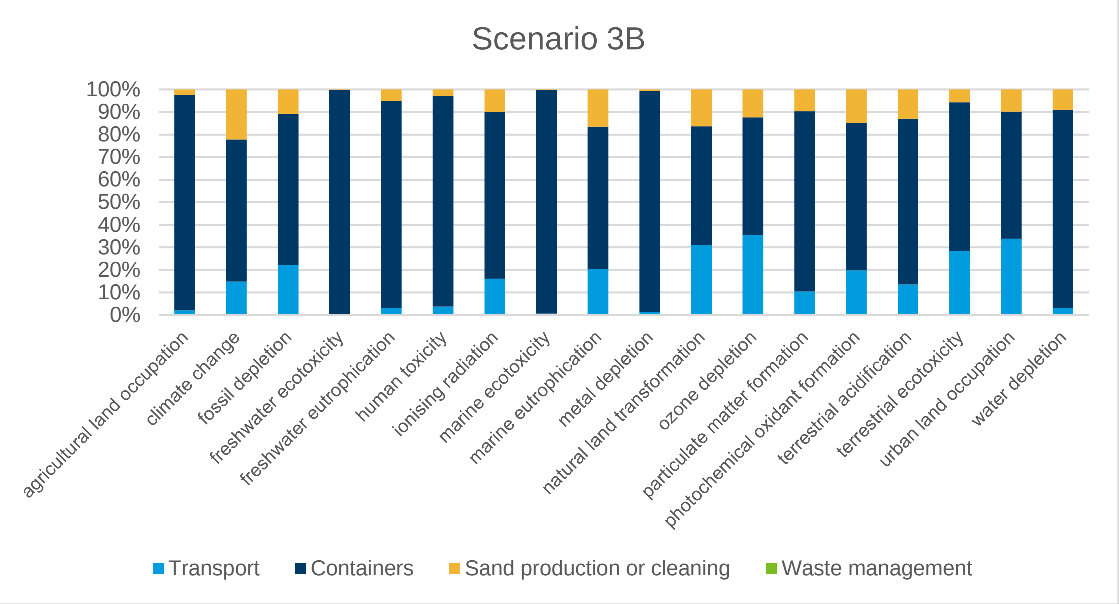

Figure 32. Hot spot results for scenario 3B.

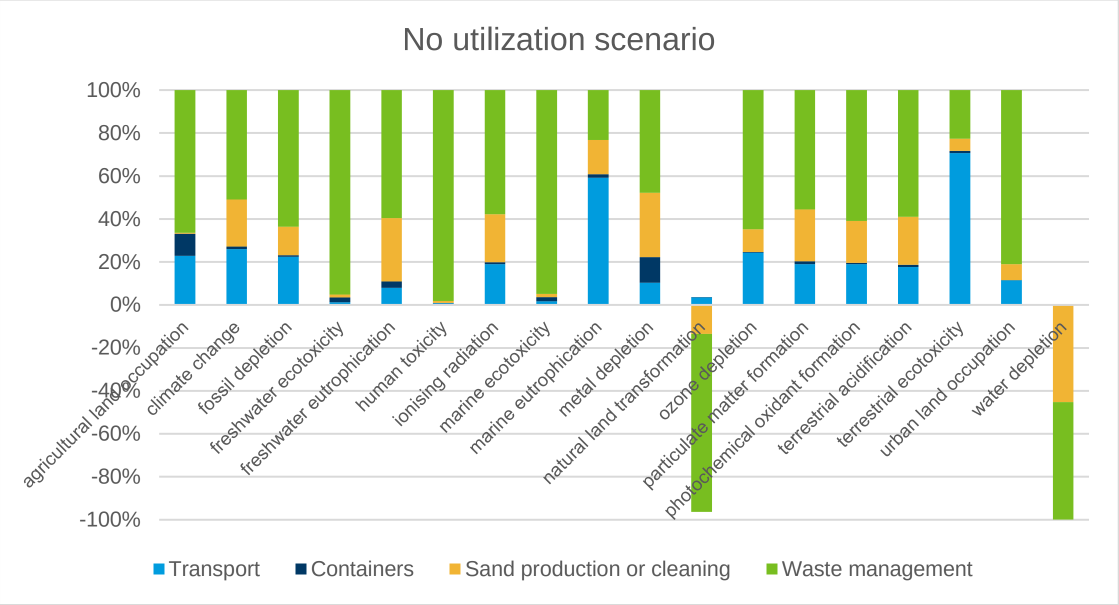

Figure 33. Hot spot results for no utilization, with negative water depletion values indicating environmental benefit.

Climate change

Scenarios 1A and 2A had the best score in this impact category, figure 34. These scenarios, where larger lorries were used to transport sand from WW facilities to the storage site resulted in smaller transport emissions compared to B scenarios and the no-utilization scenario. Container emissions were however higher due to the A scenarios using 20 foot containers instead of 10 foot as was modelled for B scenarios. Sand production or cleaning came out worse for scenarios 1A-3B due to the impacts of the concrete plan which had a higher impact per tonne sand compared to each tonne of sand quarried. Waste management (landfilling) of sand does however result in quarried sand having an overall higher impact than utilized sand in scenarios 1A, 1B and 2A. Scenarios 3A and 3B had much higher impact than all other scenarios due to a high number of containers used at the storage plan.

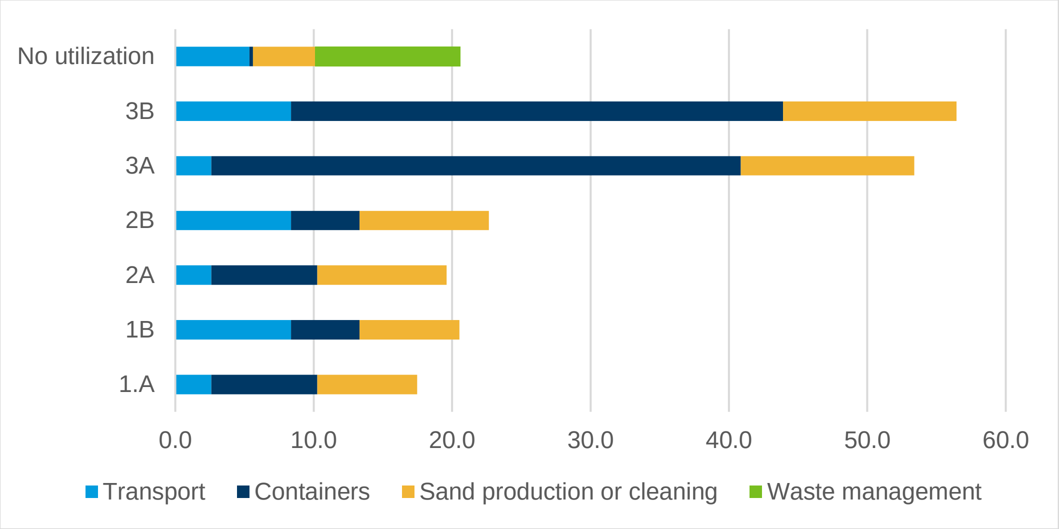

Figure 34. Hot spot analysis of the climate change effects per tonne sand between all scenarios.

Human toxicity

Scenarios 1B and 2B had the best score in this impact category, figure 35. They had less impact compared to that of scenarios 1A and 1B due to using smaller containers. No utilization had by far the worst impact with landfilling contributing to over 99% of the human toxicity impacts for that scenario.

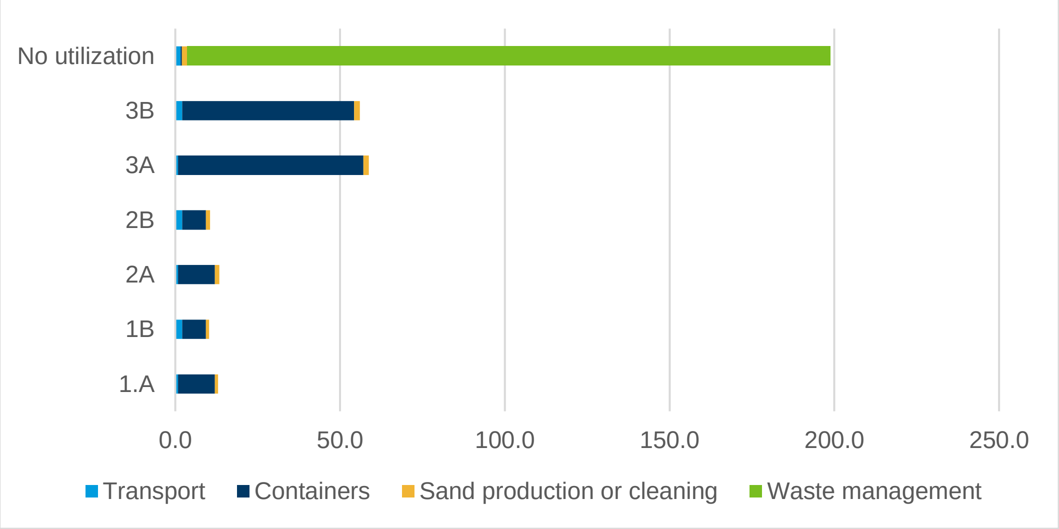

Figure 35. Hot spot analysis of the human toxicity impact per tonne sand between all scenarios.

Water depletion

No utilization scenario had the lowest and even had a positive (good) impact in the water depletion impact category. This is due to the ReCiPe method modelling additional freshwater flow into the system boundary from both the quarry operation process and the landfilling process.

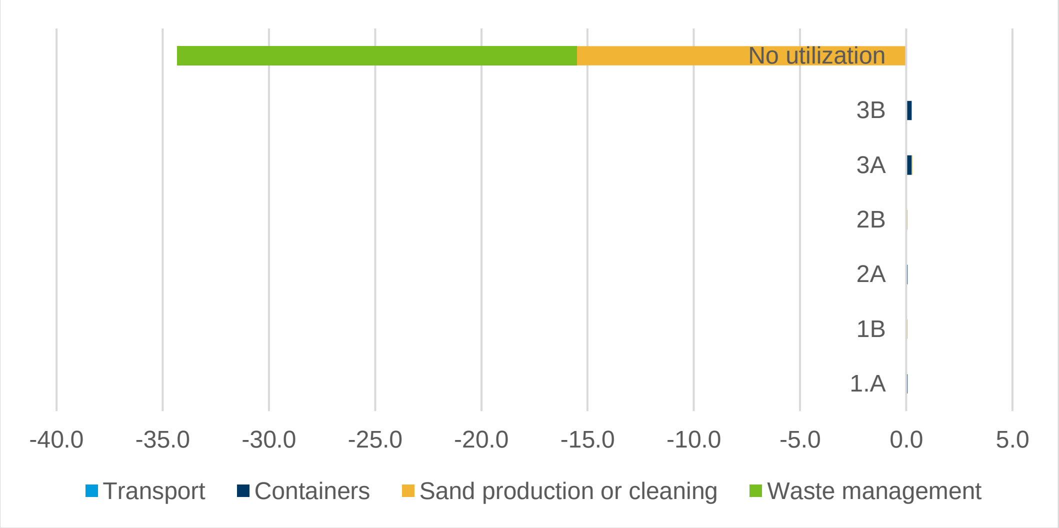

Figure 36. Hot spot analysis of the water depletion impact per tonne sand between all scenarios.

5.3.3 Sensitivity to time frames

This LCA study assumed a time frame of 25 years for the utilization system. It also assumed the lifetime of containers to be 25 years. Containers are static items processes which have a lower impact the more they are used. This was shown in the impact assessment sections above where the utilization scenarios had much higher impacts from containers since less sand was being transported with the same number of containers. Since containers turned out to contribute relatively high impacts, this can cause sensitivity of the model to which time frame (lifetime) is selected for the system. To provide a comprehensive overview of long-term effects, three time frames of 5 years (table 20), 10 years (table 21), and 25 years (table 19) are considered. These tables show the variability in the relative performance of the scenarios depending on the timeframe.

Table 20. Impact results for a 5-year timeframe.

Impact categories	Unit per tonne sand	1.A	1B	2A	2B	3A	3B	No utilization
agricultural land occupation	m2*a	6.6	3.4	6.7	3.5	31.4	28.2	0.5
climate change	kg CO2-Eq	75.8	68.1	86.5	78.8	255.4	247.7	21.5
fossil depletion	kg oil-Eq	15.3	13.9	16.6	15.1	58.9	57.4	9.6
freshwater ecotoxicity	kg 1,4-DCB-Eq	15.1	10.5	15.2	10.6	75.1	70.5	4.9
freshwater eutrophication	kg P-Eq	0.0	0.0	0.0	0.0	0.1	0.1	0.0
human toxicity	kg 1,4-DCB-Eq	61.9	42.8	63.3	44.2	290.6	271.5	200.3
ionising radiation	kg U235-Eq	4.3	3.7	4.6	4.0	17.4	16.7	2.3
marine ecotoxicity	kg 1,4-DCB-Eq	13.3	9.3	13.3	9.3	66.0	61.9	4.6
marine eutrophication	kg N-Eq	0.1	0.1	0.1	0.1	0.3	0.3	0.0
metal depletion	kg Fe-Eq	32.3	22.3	32.5	22.5	158.9	148.9	2.5
natural land transformation	m2	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
ozone depletion	kg CFC-11-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0
particulate matter formation	kg PM10-Eq	0.2	0.1	0.2	0.2	0.7	0.7	0.1
photochemical oxidant formation	kg NMVOC	0.2	0.2	0.3	0.2	0.9	0.9	0.2
terrestrial acidification	kg SO2-Eq	0.3	0.2	0.3	0.3	1.1	1.1	0.1
terrestrial ecotoxicity	kg 1,4-DCB-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0
urban land occupation	m2*a	1.3	1.2	1.4	1.3	4.4	4.2	4.6
water depletion	m3	0.3	0.2	0.4	0.3	1.4	1.3	-34.3

Table 21. Impact results for a 10-year timeframe.

Impact categories	Unit per tonne sand	1.A	1B	2A	2B	3A	3B	No utilization
agricultural land occupation	m2*a	3.3	1.7	3.4	1.8	15.7	14.2	0.4
climate change	kg CO2-Eq	39.3	38.4	44.7	43.7	129.2	128.2	20.9
fossil depletion	kg oil-Eq	8.2	8.5	8.8	9.2	30.0	30.3	9.5
freshwater ecotoxicity	kg 1,4-DCB-Eq	7.6	5.3	7.6	5.3	37.6	35.3	4.7
freshwater eutrophication	kg P-Eq	0.0	0.0	0.0	0.0	0.1	0.1	0.0
human toxicity	kg 1,4-DCB-Eq	31.3	22.4	32.1	23.2	145.7	136.8	199.4
ionising radiation	kg U235-Eq	2.3	2.2	2.4	2.3	8.8	8.7	2.3
marine ecotoxicity	kg 1,4-DCB-Eq	6.7	4.7	6.7	4.7	33.0	31.0	4.4
marine eutrophication	kg N-Eq	0.0	0.0	0.0	0.0	0.1	0.1	0.0
metal depletion	kg Fe-Eq	16.2	11.4	16.3	11.5	79.5	74.7	2.0
natural land transformation	m2	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
ozone depletion	kg CFC-11-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0
particulate matter formation	kg PM10-Eq	0.1	0.1	0.1	0.1	0.4	0.4	0.1
photochemical oxidant formation	kg NMVOC	0.1	0.1	0.1	0.1	0.5	0.5	0.2
terrestrial acidification	kg SO2-Eq	0.1	0.1	0.2	0.1	0.6	0.5	0.1
terrestrial ecotoxicity	kg 1,4-DCB-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0
urban land occupation	m2*a	0.8	0.8	0.8	0.8	2.3	2.3	4.6
water depletion	m3	0.2	0.1	0.2	0.1	0.7	0.7	-34.3

A breakeven point for each impact category is presented in figure 37. This figure shows how long a timeframe is required for any of the utilization scenarios to perform better than no utilization. Impact categories showing a break-even point of 30 years had a higher break-even but were capped at 30 for visualization purposes.

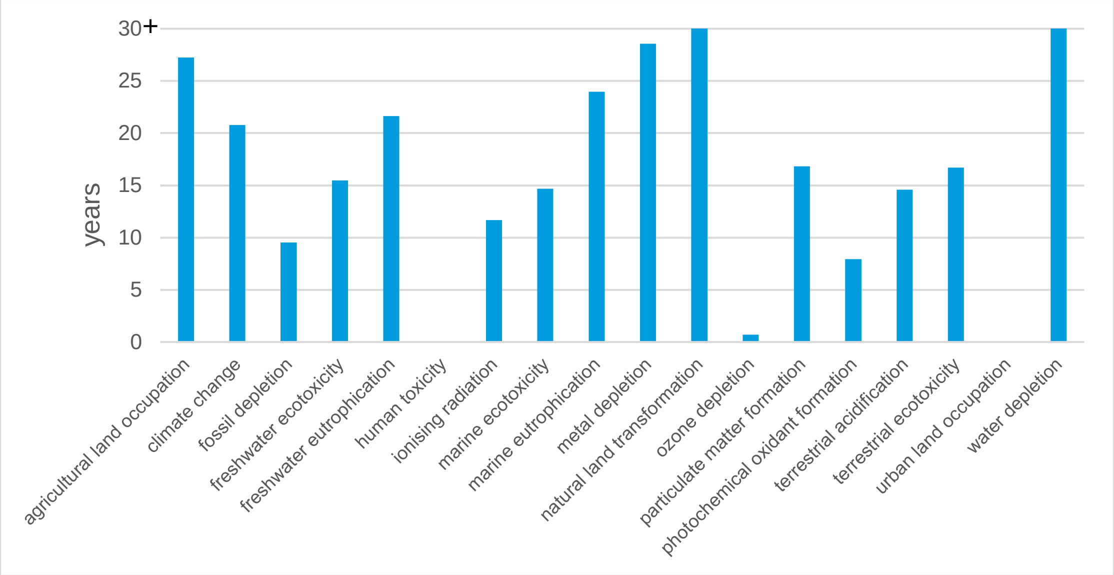

Figure 37. Break-even points describe how long a timeframe is needed for the utilization scenarios to perform better than no utilization.

5.4 LCA conclusion and discussion

This LCA compared the environmental impacts of sand utilization from wastewater facilities for a construction project and compared it to current operations where sand from wastewater facilities is sent to landfills and sand for construction projects is sourced from a quarry. The basis of comparison (functional unit) was 1 tonne of sand at the construction site. Six different scenarios were constructed for utilization, 1A, 2A, 1B, 2B, 3A and 3B. With scenarios 1, 2 and 3 differing in how sand was stored, and A and B marked different transport procedures. This was done to find the most optimal utilization model.

The result was that scenarios 1A, 1B, 2A and 2B had the lowest impact in most impact categories, however no utilization seemed to perform better in few impact categories. The break-even point was on average 16 years with the exclusion of water depletion, which had a break-even point of 4000 years.

Veitur, as outlined in its Sustainability policy (or.is) is striving to follow SDGs numbers 6, 12, 13, and 15. It is possible to align some of the impact categories with the SDGs. After 21 years, the cleaned sand from wastewater facilities starts performing better in SDG number 6 - clean water and sanitation (water depletion, freshwater ecotoxicity, freshwater eutrophication), and 13 - climate action (climate change). On the other hand, SDGs number 12 - Responsible Production and Consumption, and 15 - Life on Land are supported by impact categories such as natural land transformation, ozone depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification, terrestrial ecotoxicity, and urban land occupation. These impact categories have a break-even point of 20 years outside of natural land transformation, which has a break-even point of 180 years.

It is believed that the results obtained accurately represent the scenarios envisioned for future implementation. However, there may be some uncertainties since the scenarios were designed to maximize efficiency, yet there is no guarantee that they can be implemented exactly as designed. Additionally, it was observed that the current operational state allows for more variability, making it challenging to precisely model the 'no clean' scenario to fully represent the current situation. As such, some level of uncertainty might arise, potentially leading to deviations from real-life situations.

In conclusion, assuming a 25-year time frame, sand utilization for the purpose of applying the sand as filling material around wastewater pipes performs better in most impact categories than landfilling sand from wastewater facilities and in turn source sand for filling material form quarries.

6 Summary

- No correlation can be seen with temperature and number of fecal bacteria.
- The fastest experimental storage period for microbiota to diminish below boundary limits of 100 fecal bacteria per g was 56 days in a container 10 from Klettagarðar, less than two months. The longest experimental storage period was 511 days for container 3 from Ánanaust, the values diminished from 24 million/g to 250/g in 1 year and 5 months.
- The chemical values for heavy metals were significantly low and well within limits when compared to regulations 799/1999 and 1400/2020. Comparison to limits in regulation 796/1999 are shown on figures and might be rather strict and illogical since sand is not in direct contact to open water body, it would always leach through bedrock material and soil before reaching open water bodies.
- The washed sand from Ánanaust contains higher content of organic matter and nutrients compared to the washed sand from Klettagarðar, causing micro biota to persist longer. This results in a longer storage period for the Ánanaust sand before it can be utilized. It might thus be more beneficial to store the sand from the two treatment plants separately.
- Based on data from geotechnical testing, the washed sand is not incompatible for utilizing along electrical cables. The grain size distribution is suitable, but the thermal resistance is too high, most likely due to high organic content in the sand. However, the washed sand is feasible to utilized along wastewater pipes.
- LCA results show that utilization (scenarios 1A-2B) of sand performs better than no utilization for most impact categories, assuming a 25-year time frame. There were, however, some impact categories which showed a lower impact from no utilization.

7 References

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