Determining the Optimal Treatment for Contaminated Dredged Sediment using MCDA and LCA

Master's thesis in Industrial Ecology Programme

ISSA HERMZ, ERIK VIKTOR PYMAY

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISON OF WATER ENVIRONMENT TECHNOLOGY

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025
www.chalmers.se

MASTER´S THESIS 2025

Determining the Optimal Treatment for Contaminated Dredged Sediment using MCDA and LCA

ISSA HERMZ, ERIK VIKTOR PYMAY

Department of Architecture and Civil Engineering
Division of Water Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025

Determining the Optimal Treatment for Contaminated Dredged Sediment using MCDA and LCA
ISSA HERMZ, ERIK VIKTOR PYMAY

Supervisor: Anna Norén, CTH (Division of Water Technology)
Examiner: Ann-Margret Hvitt Strömvall, CTH (Division of Water Technology)

Master´s Thesis 2025
Department of Architecture and Civil Engineering
Division of Water Technology
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone + 46 (0)31-772 1000

Determining the Optimal Treatment for Contaminated Dredged Sediment using MCDA and LCA
Issa Hermz, Erik Viktor Pymay
Department of Architecture and Civil Engineering
Division of Water Technology
Chalmers University of Technology
Gothenburg, Sweden 2025

Abstract

Contaminated sediments that have been dredged are impacted by industrial, agricultural, and urban activities, and present health and environmental risks due to pollutants like Potentially Toxic Elements (PTEs) and organic pollutants. Treatment methods are crucial, as after the dredging process, one end of the life point is the disposal of the sediment back into the sea. If the sediment is not treated for TBT, the current regulation dictates that the sediment must be disposed of in landfills, of which availability is more scarce compared to the sea. The study provides guidance on selecting sustainable sediment treatment methods that balance environmental impacts and organic pollutant removal. This study evaluated four sediment treatment methods: Fenton + Photoelectrocatalysis (PEC), Fenton at pH 3, Methanol + Ultrapure Water + PEC, and Density Separation + PEC. The evaluation uses a Comparative Life Cycle Assessment (CLCA) and Multi-Criteria Decision Analysis (MCDA). The goal of the study is to determine the most sustainable treatment method to remove tributyltin (TBT) from 1 ton of dredged sediment. The results indicate that the treatment method including the Fenton process, particularly Fenton + PEC, achieves high TBT removal, but generates environmental impacts due to energy and chemical use, with hydrogen peroxide production being a major contributor. Methanol + Ultrapure Water + PEC is impactful due to the production of methanol; this contributes to Eutrophication. Density Separation + PEC shows the lowest environmental impact, driven mainly by salt usage and resulted in the most sustainable option according to the MCDA results. Improvement points include using renewable energy, process integration, and closed-loop systems for better recourse efficiency and process development.

Keywords:
Tributyltin, Dredging, Contaminated Sediment, Treatment, Life Cycle Assessment, Multi Criteria Decision Analysis

Acknowledgements

The authors wish to express special gratitude towards Anna Norén for constant support and constructive supervision, Yvonne Andersson-Sköld for the additional consultancy, Kristina Bernstén for the auxiliary information regarding the port of Gothenburg, Ecoinvent for using their LCA database for free for research purposes, and all other experts that patiently helped us get the information we needed to finalize this study.

List of abbreviations

CH_3OH - (Methanol) Methyl Alcohol
CH_4 - Methane
CO_2 - Carbon Dioxide
CTUe - Comparative Toxic Unit for ecosystems
DALYs - Disability-Adjusted Life Years
DBT - Dibutyltin
GWP - Global Warming Potential
H_2O_2 - Hydrogen Peroxide
HCl - Hydrochloric Acid
LCA - Life Cycle Assessment
LC_{50} - Lethal Concentration 50%
LOEC - Lowest Observed Effect Concentration
MBT - Monobutyltin
MCDA - Multi-Criteria Decision Analysis
NaCl - Sodium Chloride (salt)
NaOH - Sodium Hydroxide
NOEC - No Observed Effect Concentration
NO_x - Nitrogen Oxides
PEC - Photoelectrocatalysis
PTEs - Potentially Toxic Elements
SO_2 - Sulphur Dioxide
TBT - Tributyltin
TPT - Polytrimethylene Terephthalate
VOCs - Volatile Organic Compounds

Table of content

1. Introduction

The first chapter of the report provides an overview of the study, beginning with the aim of the chosen research area. It also introduces the project's primary objectives and the desired outcome. The chapter also includes study questions to guide the research and sets boundaries to clarify the scope and limitations of the study.

1.1 Background on Sediment Management

Sediment that has been contaminated pose significant environmental challenges due to its high concentration of pollutants, such as potentially toxic elements and organic compounds (Kamei, 2023). Dredging sediments is essential for maintaining navigable waterways and could be done to remove pollutants, but the disposal of the dredged sediment requires careful consideration due to its potential hazardous impacts on Human Health and the ecosystem (Pedersen et al., 2017). Contaminated sediment could be treated with various methods, each with its own advantages, disadvantages, and environmental implications (Liu et al., 2024). In this report, considerations about using no treatment method at all will also be included. The dredged sediment has several end-of-life points, the currently most common being deposition at landfills, without any prior cleansing. Treated sediment, however, can be deposited at deep-sea deposits, or re-used in infrastructure and buildings, as an addition to concrete. There are other organic pollutants present in the sediment that are to be extracted, either due to their toxic effects or potential re-usage (Svensson et al., 2021). While the focus of this study is solely on TBT, treatment of sediment implies also removing other toxic material, but also extraction of valuable material such as metals, and can be part of so-called urban mining, contributing to a circular economy (Svensson et al., 2021).

1.2 Aim

The aim of this study was to evaluate and compare both the effectiveness and environmental impact of different treatment methods for contaminated dredged sediment. The study aimed to assess the reduction of the compound tributyltin (TBT), a highly toxic compound often found in sediments, using four different treatment methods (Pedersen et al., 2017). The methods are Fenton + Photoelectrocatalysis, Methanol + Ultrapure Water + PEC, Fenton at pH 3, and Density Separation + PEC. By conducting a Life Cycle Analysis (LCA) and a Multi-Criteria Decision Analysis (MCDA), the study seeks to provide insights into the most sustainable and effective treatment options for managing contaminated sediment (Norén et al., 2022).

1.3 Study Questions

1. What are the environmental impacts of each treatment method, including potential effects on the chosen criteria?
2. Which treatment method is the most sustainable based on LCA and values achieved at a stakeholder's workshop?
3. What are the main improvement points regarding the sustainability of the methods?

1.4 Boundaries

The geographical boundaries focus on dredged sediment management in Gothenburg, Sweden (Magnusson & Bergkvist, 2020). The system boundaries cover the process from sediment dredging in the port of Gothenburg to disposal at sea in the deep-sea deposit next to Vinga, just outside of Gothenburg. The focus on environmental impacts during treatment, considering that both short and long-term effects only take into consideration the treatment of TBT and not PTEs or minerals for extraction (Svensson et al., 2021). The four treatment methods are investigated and developed at Chalmers University of Technology (Chalmers), and therefore, the study limits itself only to these methods. The treatment methods do not remove all TBT and some of them cannot remove TBT to the content limit as the stated regulations. In practice, the methods probably suffer from diminishing effectivity with lower concentrations of TBT, but for the sake of the study, an assumption is made that the required amount of work to clean a certain amount of TBT has a clear exponential correlation, meaning that in order to remove an x additional amount of TBT, a selected method had to be used proportionally y amount more (Norén et al., 2022). As the treatment methods have only been done in a laboratory setting, the data used in the LCA was taken from those small-scale experiments, and scaled up linearly, while in reality scaling up the processes will probably result in different inputs and outputs, some decreased and some increased, in ways that cannot be predicted (Andreottola et al., 2010). While the LCA and the study are bound to be applied geographically in the region of Gothenburg Municipality, much of the data used was already available datasets from Ecoinvent, which does not have good data available representing Swedish industry and infrastructure. Much of the data, however, was used for European standards as proxies, but a few data points used are worldwide averages. The only data verified empirically is that of distances travelled in transportation and costs for dredging in Gothenburg, and the inputs needed for the method. Any impact on the marine environment is assumed to be made in the sea, and not in freshwater, as the city of Gothenburg is just next to the sea, and all water used during the sediment treatment is assumed to end up there. The concentration of TBT in water depends on leaching from the sediment (Stewart & de Mora, 1989) and as a direct release of new TBT straight into the water is limited according to EU Regulation (EC) No 782/2003 and Directive 89/677/EEC (Commission of the European Communities, 2009), the concentration in water is highly correlated with the concentration in the sediment. For this reason, this study treats the sustainability criteria “Water Quality” and “Sediment Quality” as one sustainability criteria, as it is assumed that they will have linearly the same values.

2. Background/Literature study

In this part of the thesis, the background of dredging contaminated sediment and the findings in the literature study are described. This information was collected by conducting literature studies in combination with a workshop with experts across various fields relevant to the study area such as representatives from geological institutions, the Port of Gothenburg and academia.

2.1 Dredging

Dredging is the process of removing sediments, debris, and other materials from the bottom of bodies of water such as rivers, lakes, harbors, and oceans. It plays a critical role in maintaining navigable waterways, supporting port operations, protecting against flooding, and enabling various construction projects. Dredging is essential for maritime trade and environmental management, ensuring that shipping channels remain open, and ecosystems are protected or restored (Norén et al., 2022). There are several methods of dredging, each suitable for different applications and environmental conditions. Mechanical dredging uses machinery like clamshell dredgers, backhoe dredgers, and bucket dredgers to physically scoop material from the seabed. Mechanical dredging is often used in ports, rivers, and ports where precise sediment removal is necessary. It is particularly effective for removing hard materials like rocks and debris (Svensson et al., 2021). While dredging is essential for many economic and environmental purposes, it can also pose significant risks to marine and aquatic ecosystems as dredging activities can stir up sediments, releasing organic pollutants into the water column and affecting water quality. This can harm aquatic life, especially in areas with sensitive habitats. The risk is elevated if the sediment is contaminated, like in the case of sediment next to ports (Svensson et al., 2021).

2.2 Gothenburg and Gothenburg's Port

The city of Gothenburg is located close to three of the Scandinavian capitals, Oslo, Copenhagen and Stockholm. Over time, this has made the Port of Gothenburg the largest in Scandinavia, harboring 50% of Swedish container traffic and 30% of the container traffic of Scandinavia[1] as seen in Figure 1. The Port of Gothenburg serve an estimated 1.6 trillion Swedish Crowns worth of goods (Göteborgs Hamn, 2017). The port handles 242,000 twenty-foot equivalents and is the only port in Scandinavia which can receive the world's largest ocean-going vessels. The port stretches 13 km across the city and its municipality and employs 22.000 people (Göteborgs Hamn, 2017).

---

[1] Personal communication, Kristina Bernstén 27 May 2024

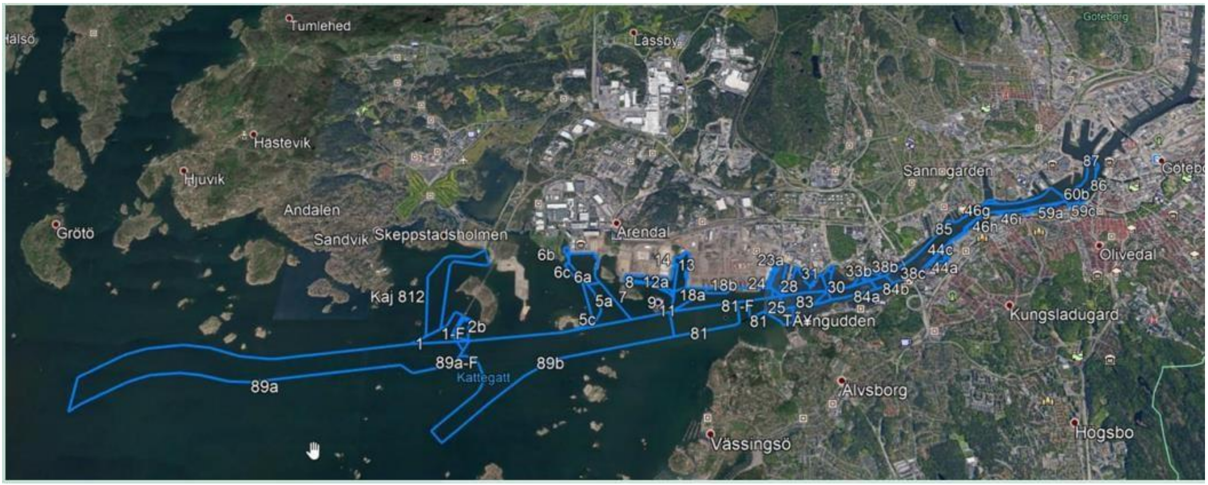


Figure 1: The Port of Gothenburg's geographic area coverage[1].

Maintenance of the port includes dredging the sediment, which in the case of the Port of Gothenburg is 200.000 theoretical solid cube meters (tfm^3) every five years of mostly clay and silt particles. Approximately 50% of the sediment is contaminated and cannot be disposed of at sea, and thus 100.000 tfm^3 of sediment must be stored on land in landfills[2].

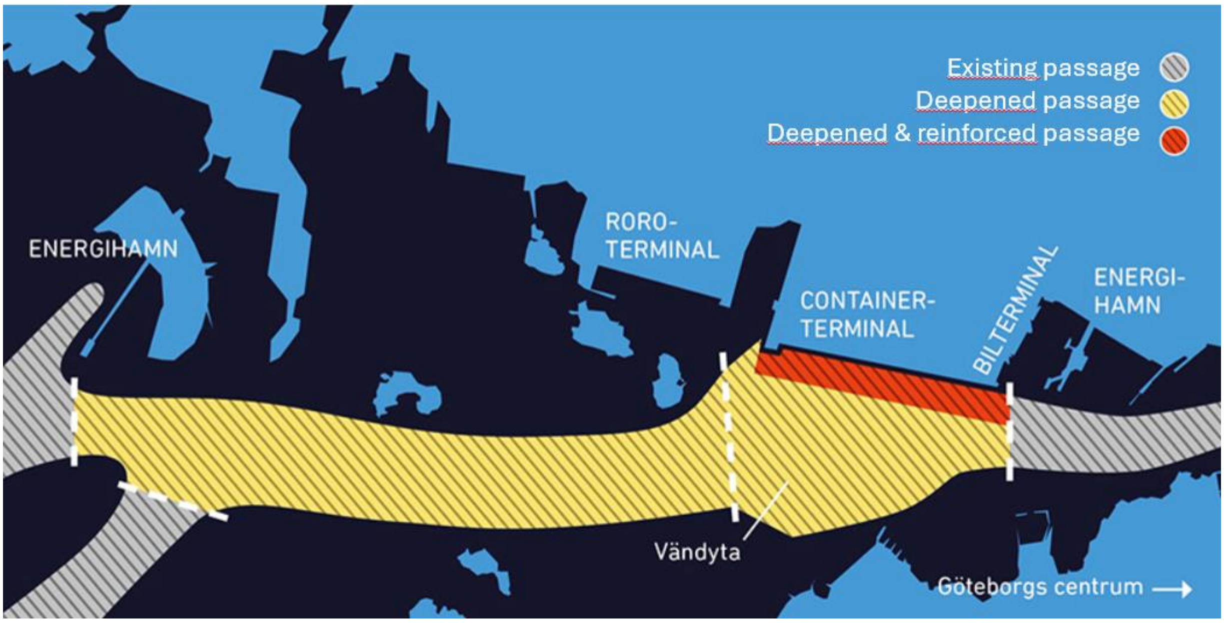


Figure 2: The planned location for the project of Scandiaporten[2].

The Port of Gothenburg is performing a big project, called the Scandiaporten, which aims to make the Port of Gothenburg capable of accepting an increased number of ships. One of the parts of the project is to deepen the riverbank in places to accommodate the bigger ships, from 13.5 meters to 17.5 meters as seen in Figure 2. This excavation will result in a displacement of 13.000.000 tfm^3 of sediment of which 200.000 to 300.000 of that sediment is considered not safe to dispose of at sea.[2].

---

[2] Personal communication, Kristina Bernstén 27 May 2024

2.3 Tributyltin, TBT

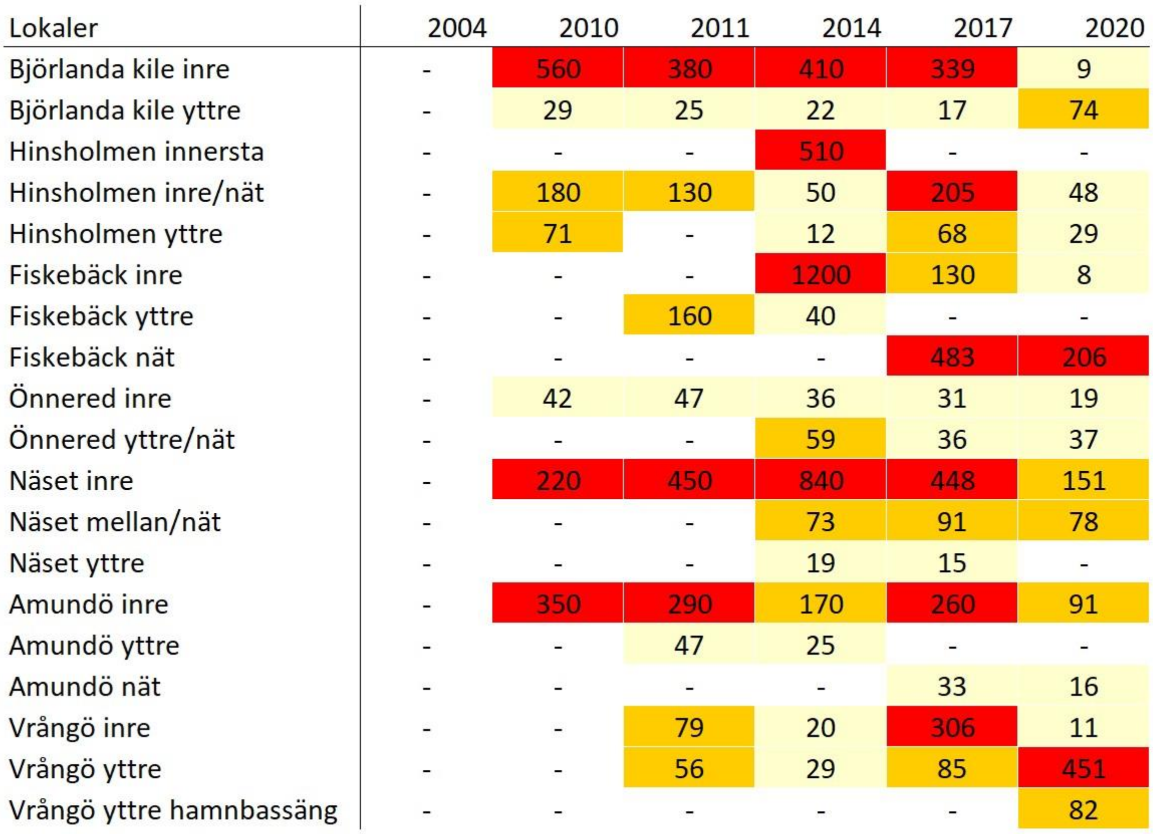
Organotin compounds, especially tributyltin (TBT), used to be of high importance as an antifouling agent in the maritime industry (Olushola et al., 2012). Between the 1950s and 1980s, the manmade product TBT was used at a large scale as the main active biocide in antifouling paints. However, the toxic effects of TBT were identified, and the compound was revealed to be an endocrine disruptor and have a similar toxicity to the better-known polychlorinated dibenzodioxin compounds (Sousa et al., 2013). The TBT degradation products, dibutyltin (DBT), and monobutyltin (MBT), also have toxic properties but to a lesser extent, in the order of MBT < DBT < TBT (Hoch, 2001; Ayanda et al., 2012) and lastly deteriorates into nontoxic tin (Sn).

In Europe, the use of TBT in antifouling paint was banned for application to small ships in the late 1980s, and to large vessels in 2003 according to EU Regulation (EC) No 782/2003 and Directive 89/677/EEC (Commission of the European Communities, 2009). Despite the ban, persistent TBT is still present in the environment, and in dark and anoxic conditions, such as in sediments at greater depths, the reported half-life spans from 10 to 90 years (Dowson et al., 1996; Viglino et al., 2004). Previous assessments of TBT degradation have indicated that the compound has a low persistence in the water column (Unger et al., 1988). In natural waters, TBT has a short residence time, with a half-life in the range of several days to several weeks (Stewart & de Mora, 1989), whereas degradation studies of TBT associated with sediments suggest half-lives at least an order of magnitude longer than those found in water. As TBT exhibits a tendency to accumulate in sediments, TBT degradation processes in sediments are more likely to control the overall persistence of TBT in the environment (Stewart & de Mora, 1989).

The acceptable daily intake (ADI) of the World Health Organization for a compound called triphenyltin TPT, exerts similar toxicities to humans and organisms in the environment as TBT (Sekizawa 2003) is 0.5 µg TPT/kgbw/day, which corresponds to 37.5 µg/day for a person of 75 kg. Since TPT and TBT exert similar toxicities in the environment, it is assumed that the same ADI can be used for TBT, which is 37.5 µg/day for a person of 75 kg. However, it is difficult to estimate how much the No Observed Effect Concentration (NOEC) (James, 2016) of TBT for humans would be, and thus this data cannot be reliably used for quantitative studies. Lethal Concentration dose 50% (LC_{50}) (Canadian Center for Occupational Health and Hazard, 2024) values for various marine organisms have been studied and different organisms react differently to TBT. Significant reductions in the growth of larval inland silverside *Menidia beryllina* were noted at 0.93 µg/L. There is an extensive dataset for marine invertebrates, with 96-hour LC_{50} values ranging from 0.42 µg/L for *Acanthomysis sculpta* to 19.5 µg/L for *Palaeomonetes pugio*. Chronic LOECs as low as 0.023 µg/L have been reported. The dogwhelk *Nucella lapillus* exhibited a high percentage of imposex at 0.019 µg/L (James, 2016). The state of Australia has as a guideline with a freshwater low-reliability trigger value of 2 ng/L and a marine high-reliability trigger value of 6 ng/L. This is considered sufficiently protective in slightly to moderately disturbed ecosystems (Australian Government Initiative, 2000). The amount of TBT measured outside of the Port of Gothenburg has been recorded as being as high as 750µg/L (Magnusson, 2020) making it 1500 to 750.000 times more concentrated than the

NOEC for the ecosystem. These spikes are at sites that are historically associated with shipping activities, but which are now used for the public as swimming resorts, for example, Näset or Fiskebäck as showed in Table 1.

Table 1: Concentration of TBT, in µg/L, at various sites in Gothenburg across several years, from the study by the Gothenburg Institute for Environmental Management. The red color indicates values posing a very high risk to the environment, the orange indicates values posing a high risk to the environment, and the yellow color indicates a medium risk to the environment (Magnusson, 2020).



Lokaler	2004	2010	2011	2014	2017	2020
Björlanda kile inre	-	560	380	410	339	9
Björlanda kile yttre	-	29	25	22	17	74
Hinsholmen innersta	-	-	-	510	-	-
Hinsholmen inre/nät	-	180	130	50	205	48
Hinsholmen yttre	-	71	-	12	68	29
Fiskebäck inre	-	-	-	1200	130	8
Fiskebäck yttre	-	-	160	40	-	-
Fiskebäck nät	-	-	-	-	483	206
Önnered inre	-	42	47	36	31	19
Önnered yttre/nät	-	-	-	59	36	37
Näset inre	-	220	450	840	448	151
Näset mellan/nät	-	-	-	73	91	78
Näset yttre	-	-	-	19	15	-
Amundö inre	-	350	290	170	260	91
Amundö yttre	-	-	47	25	-	-
Amundö nät	-	-	-	-	33	16
Vrångö inre	-	-	79	20	306	11
Vrångö yttre	-	-	56	29	85	451
Vrångö yttre hamnbassäng	-	-	-	-	-	82

The amount of TBT recorded in the Port of Gothenburg at the site of dredging is on average, 194.1 µg/kg DW, with maximal values being measured at 2000 µg/kg DW. The medial recorded is 48 µg/kg DW[3]. The measured TBT content which will be used in the theoretical models for the LCA is 124.5 µg/kg DW, a number derived as an approximated average from previous studies (Magnusson, 2020). There is currently no set regulation for TBT to be dumped into the sea, and the actual permissions issued by the government vary from case to case. At times the content of TBT per dry weight of sediment released into the sea would be 200 µg/kg DW, while in other instances, it would be 50 µg/kg DW (Bruce, 2021). In the dumping site prepared by the Port of Gothenburg for the dredging activities, the permitted limit for TBT is 50 µg/kg DW (Svea hovrätt Mark- och miljödomstolen, 2015).

---

[3] Personal communication, Kristina Bernstén 27 May 2024

2.4 Evaluated Treatment Methods for Contaminated Sediment

In this study, four methods for treating contaminated sediment and disposal at sea will be examined and compared with a baseline scenario involving no treatment method and disposal at landfill. The summary of the degradation of the different methods is shown in Table 2.

Table 2: Summary of removal efficiencies for TBT used for treatment of marine sediments with various methods.

Method	Fenton + PEC	Methanol + Ultrapure Water + PEC	Fenton at pH3	Density Separation + PEC
Percentage TBT Removed	91%	70%	67%	90%

2.4.2 Fenton + Photoelectrocatalysis

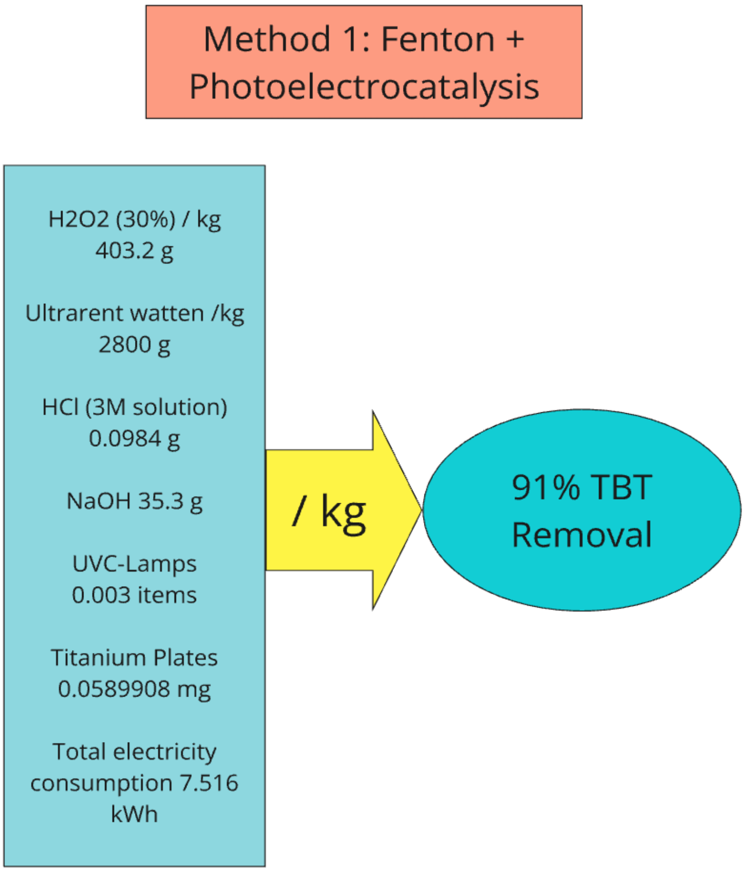


Figure 3: Overview of input requirements (chemicals, materials, and energy consumption) and pollutant removal efficiency for the sediment treatment method using Fenton + Photoelectrocatalysis (PEC).

The Fenton + Photoelectrocatalysis (PEC) method combines two treatment processes for degrading pollutants such as TBT in the sediment. Both treatment processes occur simultaneously together, with an input of titanium plates, UVC-lamps and electrical energy for the photoelectrocatalysis to start, as shown in Figure 3 (Norén et al., 2022). This results in achieving high removal rates of pollutants in the sediment. On a large scale, it can also be effective for treating heavily contaminated material, however, there are consequences for the environment as well. The method involves the Fenton reaction and photoelectrocatalysis to degrade organic pollutants in water. The Fenton reaction involves the generation of hydroxyl radicals (•OH) by the reaction between hydrogen peroxide (H_2O_2) and ferrous iron (Fe^{2+}). These compounds are highly reactive and capable of degrading organic pollutants, in this case TBT (Wang & Wang, 2020). Ferrous iron (Fe^{2+}) is naturally found in the sediment, so only H_2O_2 needs to be added (Norén et al., 2022).

Photoelectrocatalysis uses light and electrical energy to activate catalysts (titanium plates) and produce hydroxyl radicals that accelerate the degradation process. This technique could additionally recover metals. A pH adjustment is done to make the conditions right for the degradation process, using either CO_2 or acid (Introduction to Oceanography, n.d.). The chemicals here will not have any disposal, due to that they degenerate into H_2O. Also, if metal recovery is wanted from the processes, it could be done (not included in this thesis). After the treatment, the pH needs to be increased to neutral again, so one can reuse the water with neutral pH instead of acidic water, using sodium hydroxide (NaOH) for the pH adjustment, as demonstrated in the flowchart in Figure 4. Not all treatment processes occur in a sustainable way, and when looking at large-scale treatment of sediment, one needs to consider the consequences gained from the system. For example, high energy consumption, chemical usage and pH adjustment require additional treatments and costs (Andreottola et al., 2010).

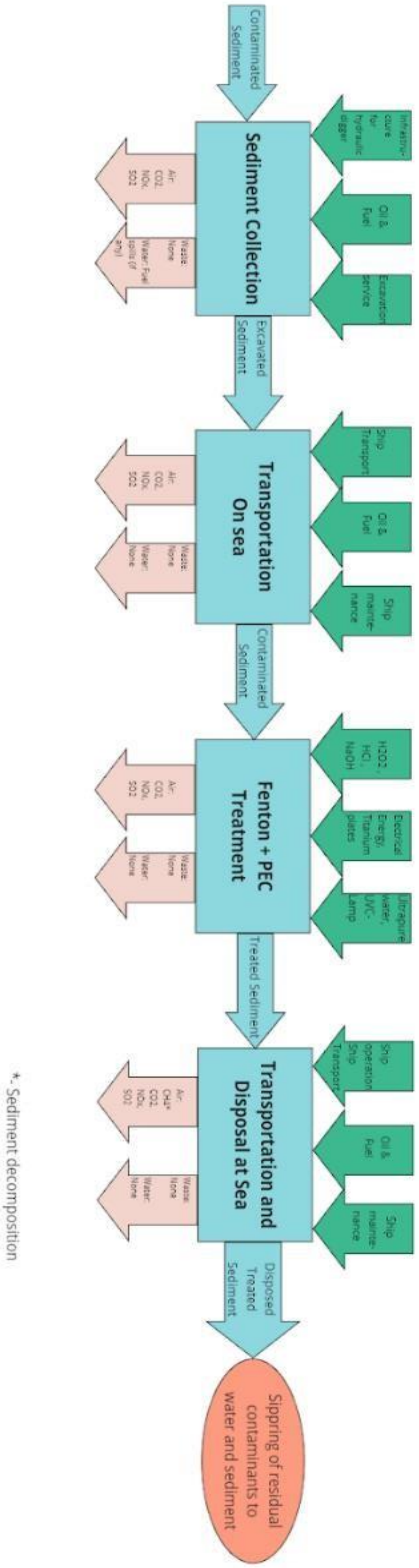


Figure 4: Flowchart describing inputs and outputs for the sediment treatment method based on Fenton + PEC.

2.4.3 Methanol + Ultrapure Water + PEC

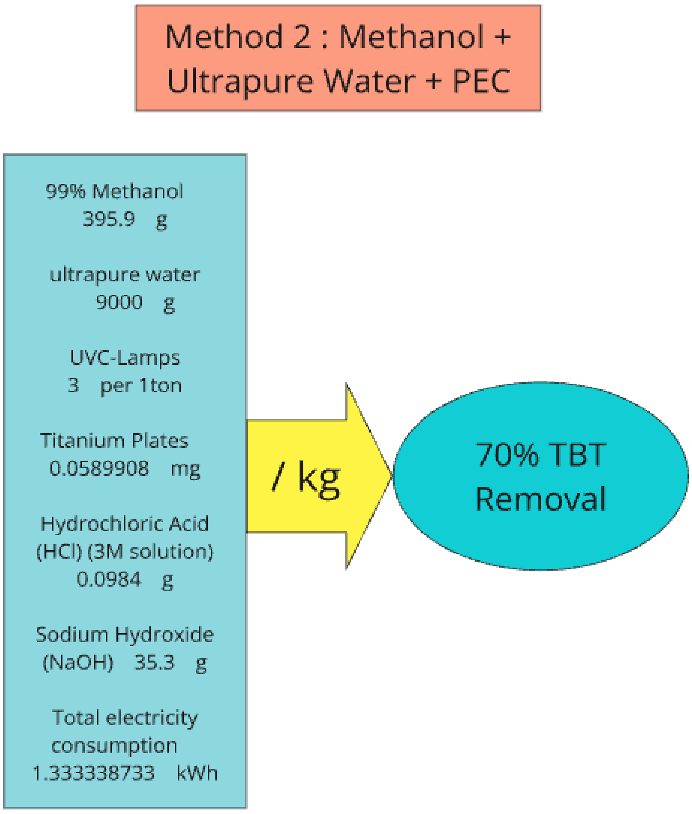


Figure 5: Overview of input requirements (chemicals, materials, and energy consumption) and pollutant removal efficiency for the sediment treatment method Methanol + Ultrapure Water + PEC.

The Methanol + Ultrapure Water + PEC method involves using a mixture of methanol and ultra-pure water to treat the contaminated sediment. The organic pollutants and other polluted organic matter are removed from the sediment through extraction with methanol and are then removed from the liquid with PEC based on oxidation. First, the process starts with a mixture of the sediment, methanol, and ultra-pure water. In the second step, an oxidation process by photoelectrocatalysis is used for degradation. The process is similar as described in 2.4.2, but the PEC is applied directly on a solution with TBT and not the entire sediment. Around 70% of the is TBT successfully removed using this method, as demonstrated in Figure 5 and Figure 6 (Norén et al., 2022). This treatment is effective for dissolving and extracting organic pollutants. Methanol is a polar solvent, meaning it is efficient for extracting TBT from sediments or water (LibreOne, n.d.). TBT is not easily solvable in water. Instead, an organic solvent is used, such as methanol, and the concentrated stock solution is diluted with ultrapure water (Tunç et al., 2021). If not done properly or in a controlled way this method could require additional treatment steps. This would lead to more chemical usage and become more costly. Chemical handling is essential here to not cause more harm to the environment. Efforts are focused on protecting marine life without compromising the integrity of other ecosystems. Methanol is a toxic and flammable solvent, meaning the waste management can be complex and hazardous for public health and ecosystems (LibreOne, n.d.)

The sediment will be released into water bodies after treatment, and it is a big risk if the measures are incorrect, and one releases even more contaminated sediment back into the ocean. All these problems above cause higher costs for larger volumes of treatment and more environmental risks if not managed right (Svensson et al., 2021).

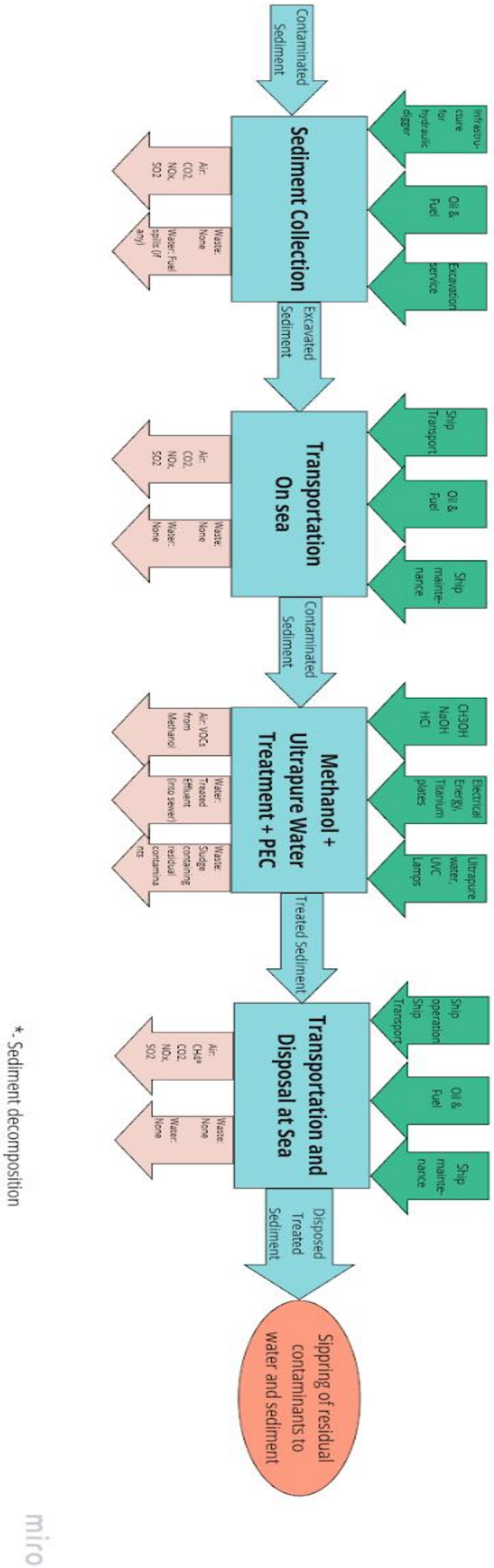


Figure 6: Flowchart describing inputs and outputs for the Methanol + Ultrapure Water + PEC method for treatment of TBT contaminated sediments.

2.4.4 Fenton at pH 3

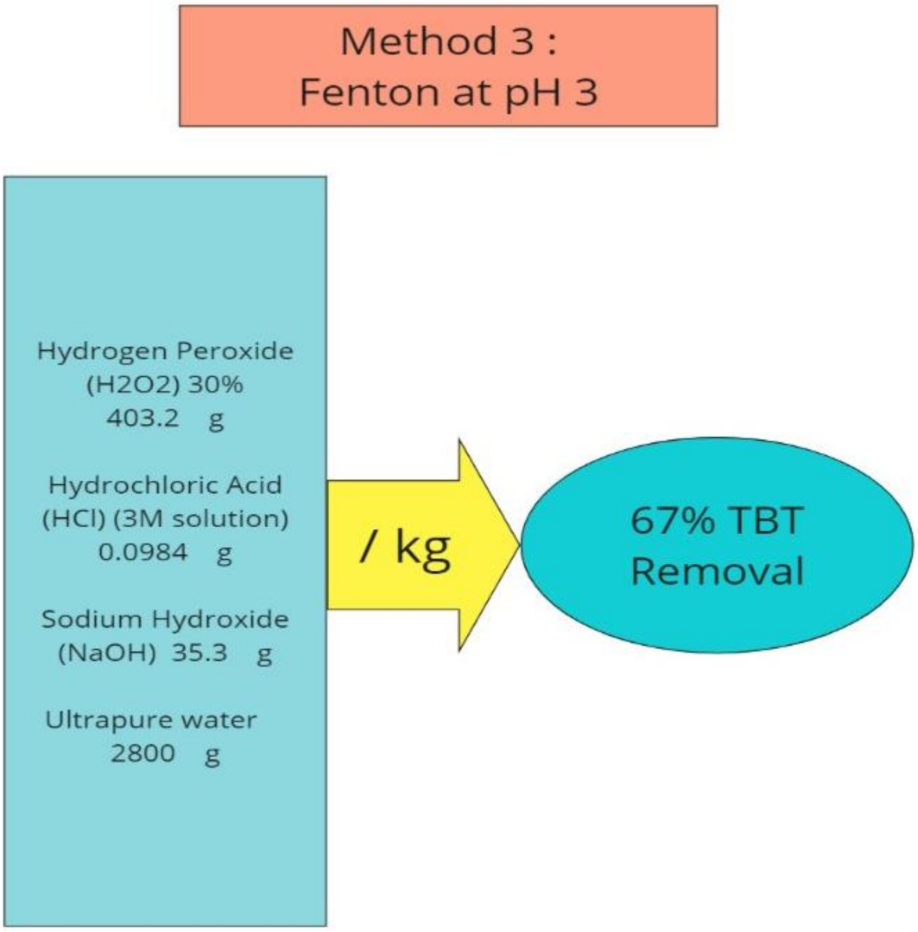


Figure 7: Overview of input requirements (chemicals, materials, and energy consumption) and pollutant removal efficiency for the Fenton at pH 3 method for treatment of TBT contaminated sediments.

The third method involves the Fenton reaction and is done at a specific pH level of 3. The Fenton process is mentioned in the first method but is done without photoelectrocatalysis here. The method is an advanced oxidation process that uses hydrogen peroxide to generate hydroxyl radicals (•OH). The method starts with pH adjustment by adding hydrochloric acid (HCI) and, thereafter, addition of hydrogen peroxide (Knapp, 2020). This later results in powerful oxidizing agents capable of degrading organic pollutants. After the treatment, the pH is adjusted to neutralize the sediment pH by adding sodium hydroxide (NaOH), as seen in Figure 8 (Bashyal, 2023). Approximately 67% of the TBT pollutants are degraded using this method, as shown in Figure 7. The effectiveness of Fenton at pH 3 is because of highly reactive hydroxyl radicals. Due to its strong oxidising power of hydroxyl radicals, the process can give quick results and an effective degradation of pollutants in the sediment. On a large scale, the same short reaction time is maintained, which efficiently treats large volumes of sediment, making it suitable for large-scale operations. (Lin et al., 2023). A disadvantage of the Fenton process is the need for pH adjustments both before and after the treatment, which can be costly and require extra chemicals (Al-Hussein, 2021). As mentioned before, more chemical usage equals a larger risk for environmental impact. Gaining some byproducts during the treatment is normal. There is also a risk of using too much hydrogen peroxide, which may cause unwanted byproducts. The biggest risks or disadvantages from this method are its cost and complexity of the chemical management (Zhang et al., 2019).

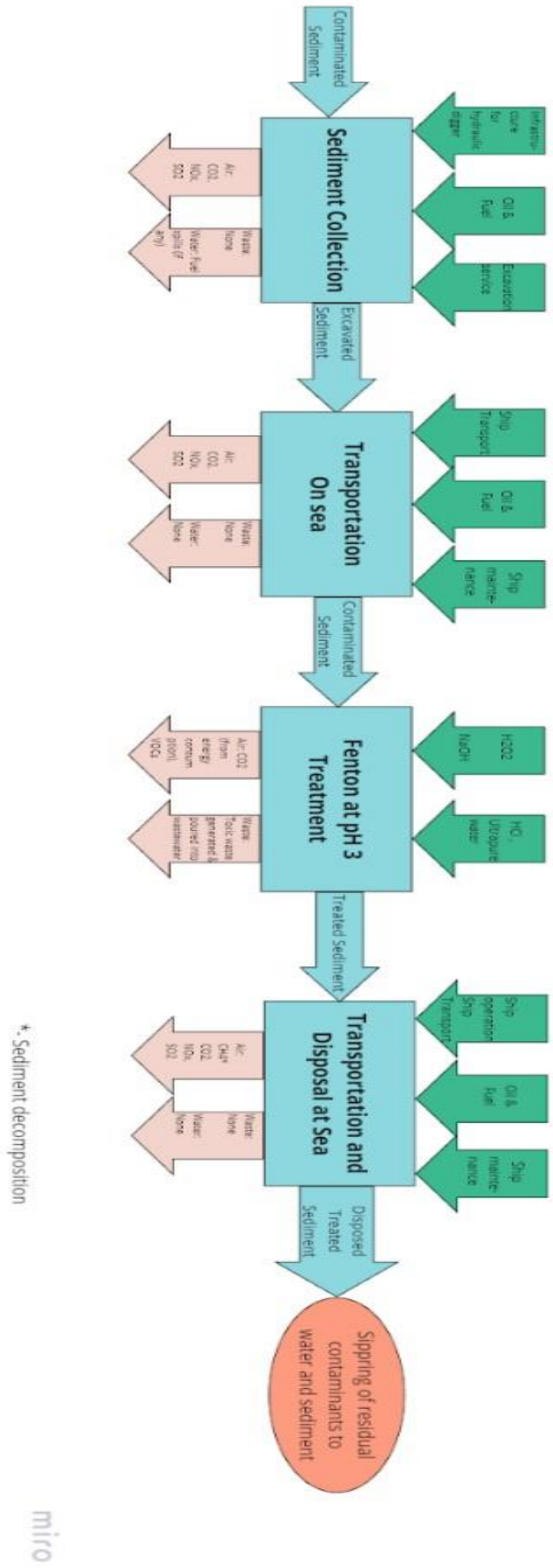


Figure 8: Flowchart describing inputs and outputs for the sediment treatment method with Fenton at pH 3.

2.4.5 Density Separation + PEC

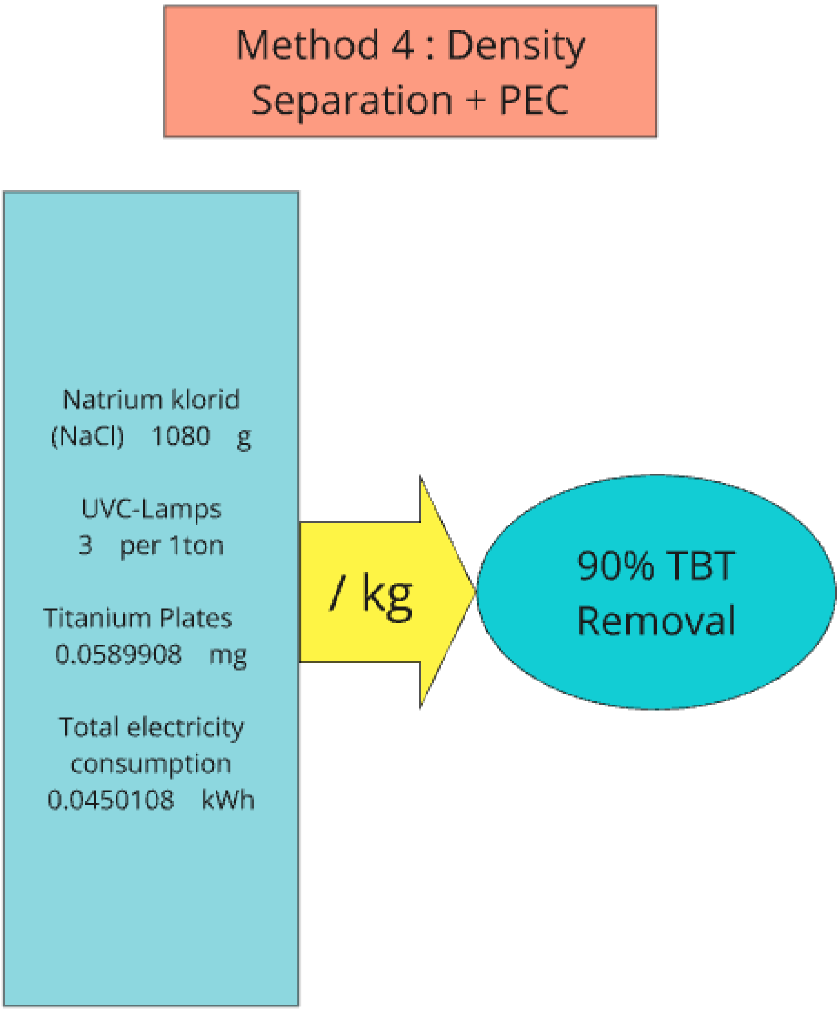


Figure 9: Overview of input requirements (chemicals, materials, and energy consumption) and pollutant removal efficiency for the sediment treatment method based on Density Separation + PEC.

This method uses Density Separation + PEC of paint flakes to remove TBT from water. Density Separation involves separating substances based on their different densities. With an estimation of a removal rate up to 90% of TBT, this method makes its way up in the ranking list side to side with method 1 (Table 2). In this process, sodium chloride is used, commonly known as edible salt, and is an ionic compound with the chemical formula NaCl. NaCl is added to the sediment slurry, causing the lower density particles such as the TBT and boat paint flakes containing TBT to be separated from heavier sediment particles, as it will be floating up to the surface. In the second step, an oxidation process by PEC is used for degradation. The process is similar as described in 2.4.2, but the PEC is applied directly on a solution with TBT and not the entire sediment. a process that degrades them and reduces their harmful effects in the water/sediment (Duong et al., 2022). Like the other methods, with an oxidation process for removing organic pollutants, the resource usage of electrical energy, titanium plates and UVC-lamps as inputs to the process (Figure 9 & Figure 10). Compared to different treatment methods, this treatment does not require complex chemicals or advanced technologies. With low chemical usages, it reduces both costs and the environmental impact (Pedersen et al., 2017). The disadvantage of this method is that Density Separation + PEC is ineffective for all types of pollutants. If the pollutant has a similar density as the sediment, it can be difficult to separate the organic pollutants from the sediment and may result in further treatment being required to achieve desired effect. Also, handling separate pollutants can be challenging and may require additional resources if not managed correctly. Density Separation + PEC can be seen as a pre-treatment process since it may not eliminate all pollutants. This causes more energy and water requirements. Although the method does not use many chemicals, it may require much energy and water if done on a large scale (Duong et al., 2022).

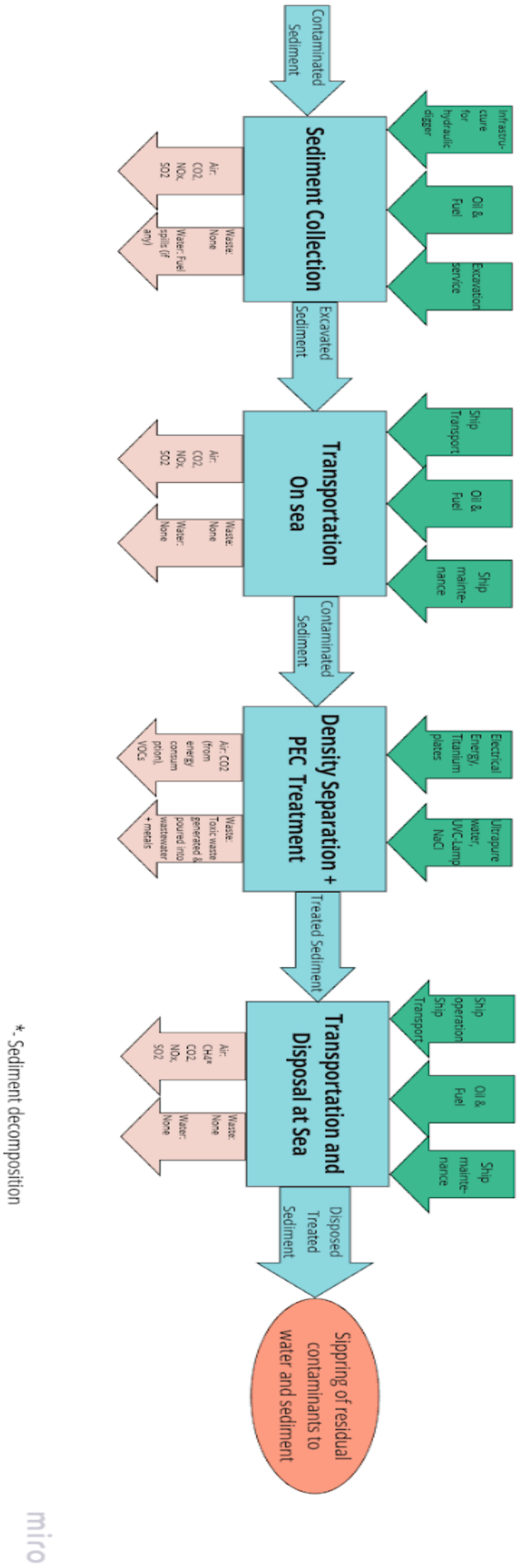


Figure 10: Flowchart describing inputs and outputs for the sediment treatment method based on Density Separation + PEC.

2.5 Sustainability criteria

Five out of seven of the sustainability criteria were assessed quantitatively through the CLCA (Climate change, Eutrophication, Acidification, Human Health & Ecotoxicity), while Sediment Quality and Water Quality were assessed qualitatively, based on literature.

Climate change - Climate change may lead to a range of impacts on ecosystems and societies, but greenhouse gases have one property in common. The characterization of greenhouse gases is based on the extent to which they enhance the radiative forcing in the atmosphere, i.e. their capacity to absorb infrared radiation and heat the atmosphere. Carbon dioxide (CO_2) is not the only gas that causes Climate change, methane and nitrous oxide gases also absorb infrared radiation. The potential contribution of a substance to Climate change is expressed as its global warming potential GWP and is measured in CO_2 equivalents. (Baumann & Tillman, 2004). As the Swedish government aims to achieve net zero CO_2 emissions by 2045 (Ministry of Climate and Enterprise, 2021), the emissions from industries, transport and households' processes such as waste management should be ideally zero (Ministry of Climate and Enterprise, 2021).

Eutrophication - Eutrophication is associated with the environmental impacts of excessively high levels of nutrients that result in shifts in species composition and increased biological productivity. In LCA this category covers not only the impacts of nutrients, but also those of degradable organic pollution. Eutrophication is measured in Nitrogen Equivalents. (Baumann & Tillman, 2004) The Swedish government has committed itself to reach a zero-emission in nitrogen and phosphorus (Johansson, 2016)

Acidity (Acidification) - Acidity refers to the concentration of oxonium ions (H_3O^+) in water. In nature, increased acidity, especially in soil and water, can have harmful effects on ecosystems. Acid rain, for example, is caused by pollutants like sulfur dioxide and nitrogen oxides that lower the pH of rainwater. This can damage plant life, erode buildings, and acidify bodies of water, leading to harmful conditions for aquatic organisms. Acidity is measured in mol H_3O^+ equivalents (Baumann & Tillman, 2004).

Water and Sediment Quality - Consists of two separate parts, Water Quality and Sediment Quality. Water Quality is the condition of the water and is important for the health of aquatic ecosystems and overall human use, such as drinking water and agriculture (Arora, 2017). In this study, the term Water Quality is related to the concentration of TBT in the water, where the amount of TBT released is assumed to correspond to 20% of the TBT in the sediment, as TBT has a low half-life relative to TBT in sediment (Stewart & de Mora, 1989). Methods that are able to purify the amount of TBT to concentrations that fall below the LC50 for the most resilient marine organisms get the highest scoring, and the methods that can purify down to the LC50 of the least resilient organisms (Australian Government Initiative, 2000) get the lowest score. There are even lower concentrations of TBT to be pursued that would benefit the ecosystems, such as the NOEC values of 6 ng/L (James, 2016) but as none of our methods come near that level of effect, they will not affect the MCDA. Sediment contamination focuses on the condition of sediments in water. This includes the presence of contaminants like toxic metals, organic pollutants, or nutrients that can affect the health of aquatic life and ecosystems.

Good Sediment Quality is important for maintaining healthy habitats for organisms living in the sediment (U.S. Environmental Protection Agency, 2023; Swedish Environmental Protection Agency, 2024). The concentration of TBT in water depends on leaching from the sediment (Stewart & de Mora, 1989) and as a direct release of TBT is limited according to EU Regulation (EC) No 782/2003 and Directive 89/677/EEC (Commission of the European Communities, 2009), the concentration in water is highly correlated with the concentration in the sediment. For this reason, this study treats Water Quality and Sediment Quality as one sustainability criteria.

Ecotoxicity - Refers to the reduction of life forms within a particular ecosystem. This includes loss of species and ecosystem complexity. This can happen due to pollution, Climate change and habitat destruction caused by land use. This later leads to the collapse of ecosystems and the loss of those services that are important for Human Health (Encyclopedia Britannica, 2024). CTUe stands for Comparative Toxic Unit for ecosystems and is used to understand values for biodiversity loss (Ecotoxicity) (USEtox Team, n.d.). A low CTUe value means that little or no biodiversity is lost and has a minimal impact on the ecosystem. However, a high CTUe value is bad, due to higher biodiversity loss (Owsianiak et al., 2022).

Human Toxicity - Is the overall health and well-being of people in a community. This examines how different environmental factors, like pollution, might impact Human Health. When protecting Human Health, one needs to ensure there is no exposure to harmful toxic substances (CDC Foundation, n.d.). Human Toxicity can be measured with a unit of DALYs and stands for Disability-Adjusted Life Years (World Health Organization, n.d.; Public Health Notes, n.d.). This unit helps us understand not just how many people are dying from diseases, but also how many are currently living with diseases that affect the quality of life. Maintaining low DALY values would be considered good, as the lower the DALY value gained, indicates a healthier population (Public Health Notes, n.d.). The source Public Health Notes (n.d.), explains that the numerical interpretation of DALY is; If DALY=0, it indicates a population with perfect health and DALY=1, its worst possible health state or death. DALYs are a useful tool for public health, but their interpretation can sometimes be challenging due to many factors that can affect the result.

3. Method

The method chapter outlines the approach used to conduct the study. It describes the research design, data collection methods, and analytical tools/techniques employed to address the research questions.

3.1 Information retrieval

To gain information for starting the work, literature studies have been made. The studies have been ongoing throughout the work and have given us knowledge about background information for base knowledge. It is good to have as many sources as possible to be sure that what is written is correct and current (Yale University Library. n.d.). The literature search is done on available databases, libraries, the internet and interviews with experts that work at Port of Gothenburg and workshop with the different experts that attended. The search was performed in several databases like ScienceDirect and Ecoinvent. The research included sediment contamination, dredging activities, studies that relate to TBT, and its ecological impacts. Also, regulatory documents and environmental assessments articles were the focus to ensure a good understanding of the subject. Some keywords that have been used are: "Sediment Treatment," "Fenton Process," "Photoelectrocatalysis," "TBT Removal," "Environmental Sustainability," "Life Cycle Assessment," and "Sustainable Dredging.".

3.2 Life Cycle Assessment

The Life Cycle Assessment (LCA) methodology employed in this study is founded on the LCA framework. This systematic approach was used to evaluate the environmental, economic, and social impacts of processes and products throughout their entire life cycle. By utilizing this method, a more comprehensive analysis of the sustainability of various sediment management strategies can be achieved (Baumann & Tillman, 2004).

The first step in an LCA involves goal and scope definition, which addresses the purpose of the LCA study. Critical questions such as Why? Who? and What? are answered, along with the overarching purpose of the assessment. Creating a flowchart to illustrate the different processes is also an essential component of this stage. Following this, the scope definition outlines the boundaries of the assessment, including the functional unit (e.g., a measure of the function or service provided by the process) and the system boundaries, which determine what is included or excluded from the analysis (Baumann & Tillman, 2004).

The second step is the Life Cycle Inventory Analysis (LCI), recognized as the most time-consuming aspect of the assessment. After the flowchart is constructed, data collection on all inputs and outputs associated with the processes is necessary. This data encompasses energy consumption, emissions, waste, and other resources (Baumann & Tillman, 2004). The LCI was conducted through the Ecoinvent database as Ecoinvent possesses a large amount of data available for LCIs (Ecoinvent, version 3.10,
2024).

The third step is the Life Cycle Impact Assessment (LCIA), which involves classification and characterization. This stage assigns the inventory data to specific environmental impact categories and quantifies the contributions of each impact category. For instance, the amount of CO_2 emitted is translated into its contribution to global warming (Baumann & Tillman, 2004).

The methods will be run in two different scenarios, one where one-ton sediment is treated with each method, as described in the experiments on which this study is based. The other scenario is when the amount of TBT is reduced to a degree of 80% of the admitted amount of TBT, 50 µg/kg DW (Svea hovrätt Mark- och miljödomstolen, 2015), meaning from an initial content of 124 µg/kg TBT to 25 µg/kg TBT (80% reduction). The focus of the study, and the detailed LCA results are all based on the methods adjusted for 80% TBT removal, but for reference the number of cycles needed for removal of 99.9% and 99.99% are shown as well. To convert to the desired reduction of TBT, the following factors were used as calculated by

$$x^y = z$$

where x is the original TBT removed predicted, z is the new rate of removal, and y is the factor, meaning the number of “cycles” the method must be used. The results are presented in Table 3.

Table 3: Comparison of various treatment methods by amount of cycles required to remove different percentages of TBT from sediment.

Method	Fenton + PEC (91%)	Methanol + Ultrapure Water + PEC (70%)	Fenton at pH3 (67%)	Density Separation + PEC (90%)
Cycles without adjustment	1	1	1	1
Cycles for 80% TBT Removed	0.66	1.33	1.45	0.70
Cycles for 99,9% TBT Removed	2.87	5.74	6.23	3.00
Cycles for 99,99% TBT Removed	3.83	7.65	8.30	4.00

The databases used for the characterization of the impact of the methods were a combination of two databases, the Environmental Footprint (EF) (European Platform on LCA, 2022), where the Climate Change, Eutrophication, Acidification, and Ecotoxicity, and Impact World + (Impactworldplus, n.d.), the “Human Health” characterization was used. The EF impact assessment method is used in this thesis report and the method is maintained by the European Commission. The method was updated from version 3.0 to version 3.1 in July 2022.

Furthermore, there is an EF v3.0 and EF v3.1 implementation for the EN 15804 standard, which differs in CFs for biogenic CO2 (European Platform on LCA, 2022). The method has an overall good variety of characterization methods which covered the impact methods selected in the first step of the MCDA. However, the Ecotoxicity was split into several geographic locations, and for the study the “Ecotoxicity, freshwater” was closest to the studied environment. The same was true for Eutrophication, where “Eutrophication, marine” was closest for the studied location. IMPACT World+ is developed by several institutions: International Reference Center for Life Cycle Assessment and Sustainable Transition (CIRAIG, 2022), University of Michigan, Quantis International, Technical University of Denmark, and école Polytechnique de Lausanne. It is a globally regionalized LCIA method, “integrating multiple state-of-the-art developments as well as damages on water and carbon areas of concern within a consistent LCIA framework (Impactworldplus, n.d.). The database contains “Human Health” as opposed to other methods, which only supplied either Carcinogenic or non-Carcinogenic human toxicity.

The penultimate step is verification and validation, which was done by having the involved stakeholders and the supervisors of this project monitor the quality of the work done.

The final part of the LCA is interpretation of the results and putting them into context, often by peer reviewing or conducting complementary discussion and research (Baumann & Tillman, 2004). In the case of this study, an MCDA was conducted based on the results of the LCA, resulting in a recommendation of which method to use to reduce the environmental impact.

3.3 Multi-Criteria Decision Analysis

The Multi-Criteria Decision Analysis (MCDA) framework was used to assess and rank the different sustainability criteria and ways to manage dredged sediment. This tool is helpful in complex situations where one must consider multiple factors. MCDA helps balance environmental, economic and social factors by combining expert opinions to find the best sustainable solution (Department for Communities and Local Government, 2009). First in the MCDA, the criteria selection was conducted, by using common sustainability characterization aspects found in literature, (Department for Communities and Local Government, 2009) and sending it out to a selected 20 representatives from either the municipality of Gothenburg, or organizations associated with the Port of Gothenburg, the dredging activity, the treatment process or supervisory institutions. The complete form can be viewed in appendix D. Based on the collected answers, a set of six sustainability aspects were derived based on the average preference of the collected form and the availability of data for the selected sustainability aspect. Examples of sustainability aspects which had a high average scoring but were not implemented in the final LCA and MCDA were economical aspects such as energy consumption, as it was deemed connected to the consumption of energy and the resulting Global Warming Potential (GWP). Eutrophication and Acidification of the environment will be considered as other aspects. The effect on the shipping industry was also excluded from consideration, as it seemed irrelevant (the dredging must anyway be conducted). Secondly, as in the form of a workshop, selected stakeholders were invited to create the final weighing criteria for the MCDA, which was to be achieved through consensus of the participants. The material used for the workshop can be seen in appendix E. The different answers were recorded and stored for the final step of the MCDA, combining the weighting criteria with the results of the LCA. The results of the LCA were converted from absolute numbers into relative comparisons. The calculation of the final MCDA result proceeds as follows: The weighting factors as established during the stakeholder workshop multiplied by the values of the impact analysis from the LCA yield and the total contribution, calculated by multiplication of the weighing factor and the impact values is shown in the "total" column.

3.4 Sensitivity analysis

To give a fair overview of which method is most sustainable, the uncertainties in the study must be addressed. The greatest sources of uncertainty in this study are the lack of relevant data for the actual geographical limitation of Gothenburg, and relying on the opinions of experts, as only eight experts were gathered. To combat uncertainty in data, different proxies were made, and alternative datasets were used. The alternatives used are presented in Table 4.

Table 4: Variations used for the inventory analysis that were changed in the sensitivity analysis.

Original value used	Altered values
Ultrapure water	Tap water
Salt for chemical industry	Food grade salt
Electricity production, Swedish market mix	Electricity production, offshore wind

4. Results

The results chapter presents the findings of the study based on the data collected and analyzed. It provides an elaborate description of the results derived from the methodologies utilized in the study. The results display percentual comparisons as result of the CLCA. The full results with absolute numbers are shown in Appendix A, B and C.

4.1 CLCA results across all impact categories

The results of the CLCA presented as a percentage representation of the treatment method that got attributed the highest impact in each characterization category. The results are presented for the methods with no adjustment, and the methods while adjusted for the same amount of TBT removed, that is 80%.

4.1.1 Results of CLCA (no adjustment)

The result of the LCA when applying the treatment methods on 1 ton of sediment and removing 91% TBT for Fenton + PEC, 70% for Methanol + Ultrapure Water + PEC, 67% for Fenton at pH3 and 90% for Density Separation + PEC, seen in Figure 11. The result in absolute numbers is displayed in Appendix A.

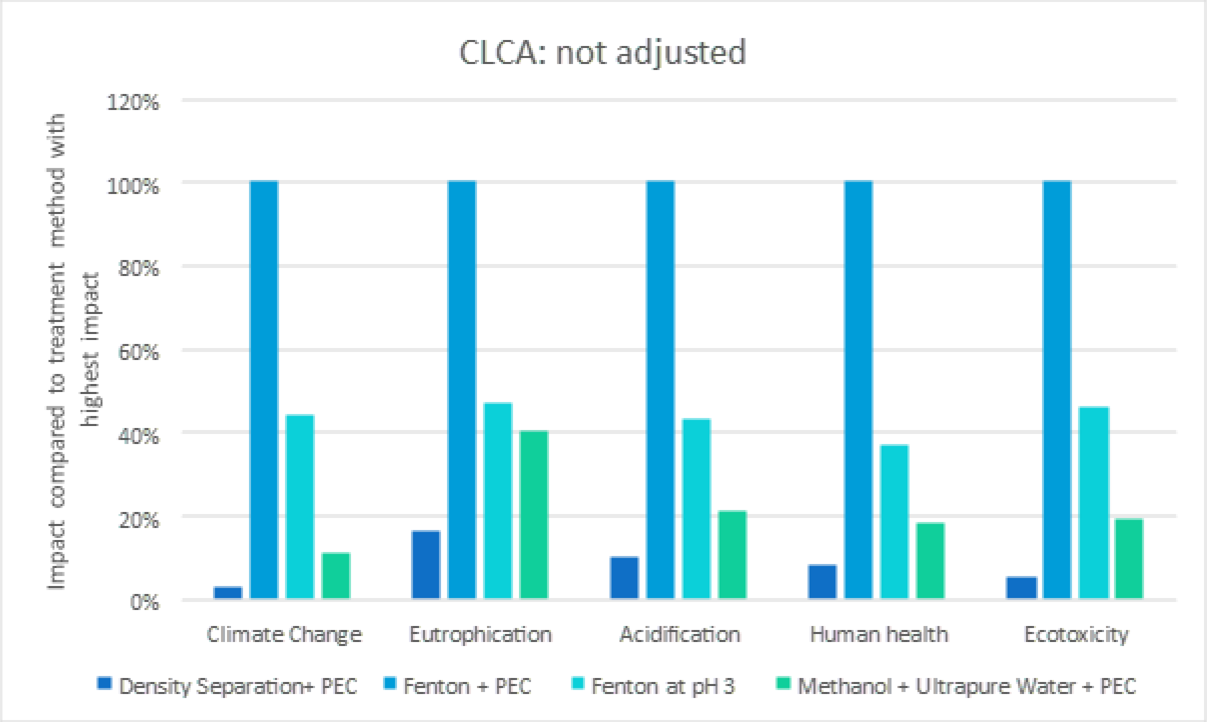


Figure *11*: Results of the CLCA for comparison of the treatment methods for sediments, with **no** adjustment to the amount of TBT removed. The results are compared to the method that has the highest impact in the given impact in each characterization category.

4.1.2 Results of CLCA (adjusted)

The result of the LCA when applying the methods on 1 ton of sediment and theoretically removing sufficiently much TBT to the recommended values of 50 µg/kg DW and effectively reducing the TBT by 80%, by running the methods linearly longer. In the case of Fenton +

PEC and Density Separation + PEC, this means reducing the number of cycles of the method, as the baseline effectiveness of those methods is already above 80% (Figure 12). The result in absolute numbers is displayed in Appendix B.

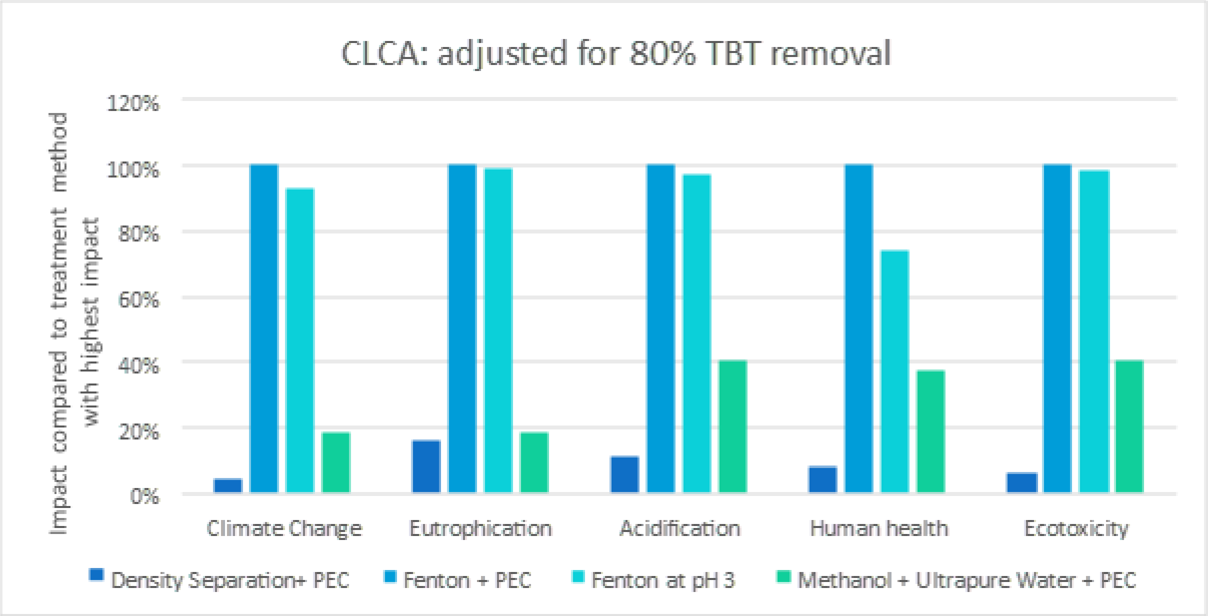


Figure 12: Results of the CLCA, for comparison of the treatment methods for sediments, with adjustment to the amount of TBT removed equal to 80%. The results are compared to the method that has the highest impact in the given impact in each characterization category.

4.1.3 Sensitivity analysis

The study has been conducted by comparing the results of the LCA with variation to some factors. Changing electricity from the normal Swedish mix available at the market to completely renewable (this case offshore wind), changing the water from ultrapure water to normal tap water and changing the quality of salt from pure salt to table salt. The result is shown in Figure 13.

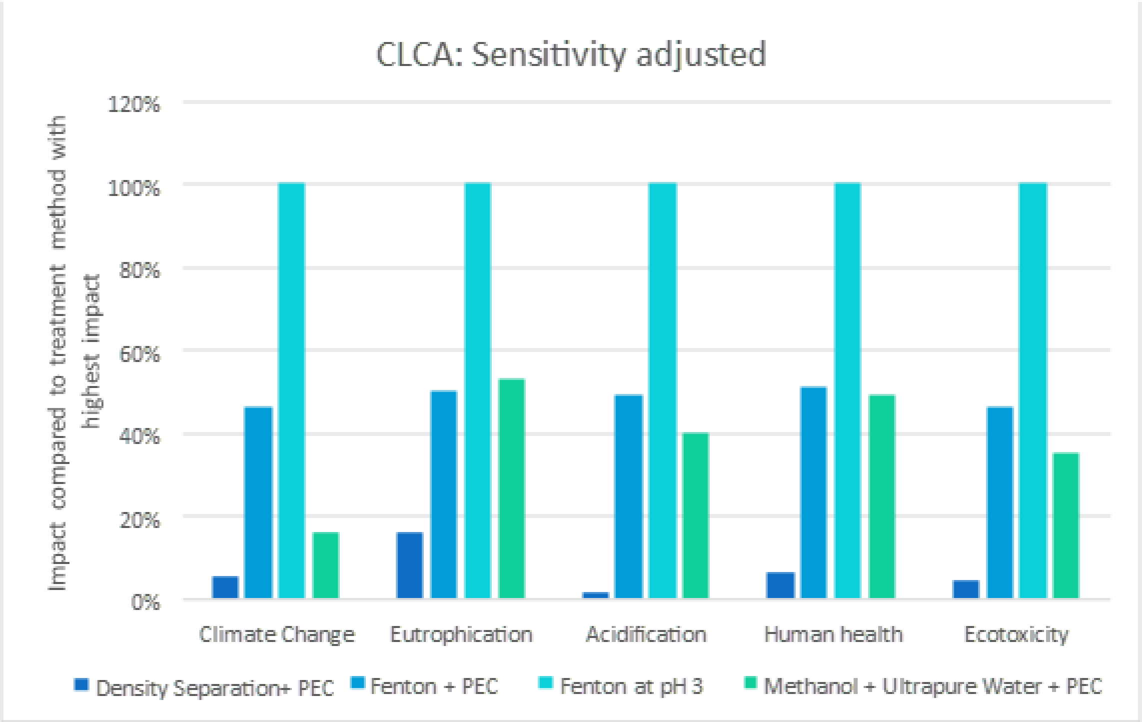


Figure 13: CLCA with values adjusted for 80% TBT reduction, for comparison of the treatment methods for sediments, with added sensitivity factors. The results are compared to the method that has the highest impact in the given impact in each characterization category.

4.2 Breakdown of contribution from individual processes

The most interesting findings from the CLCA were broken down into individual processes and are displayed below. The findings are displayed relevant to the result of the LCA when adjusted for degrading 80% of the TBT.

4.2.1 Fenton + Photoelectrocatalysis

Fenton had the highest scores across all impact categories. The largest source of the impact across all categories is the required electricity for the process. The second largest contributor is the hydrogen peroxide (H_2O_2) production. These two represent 80% to 90% of the impact (Figure 14).

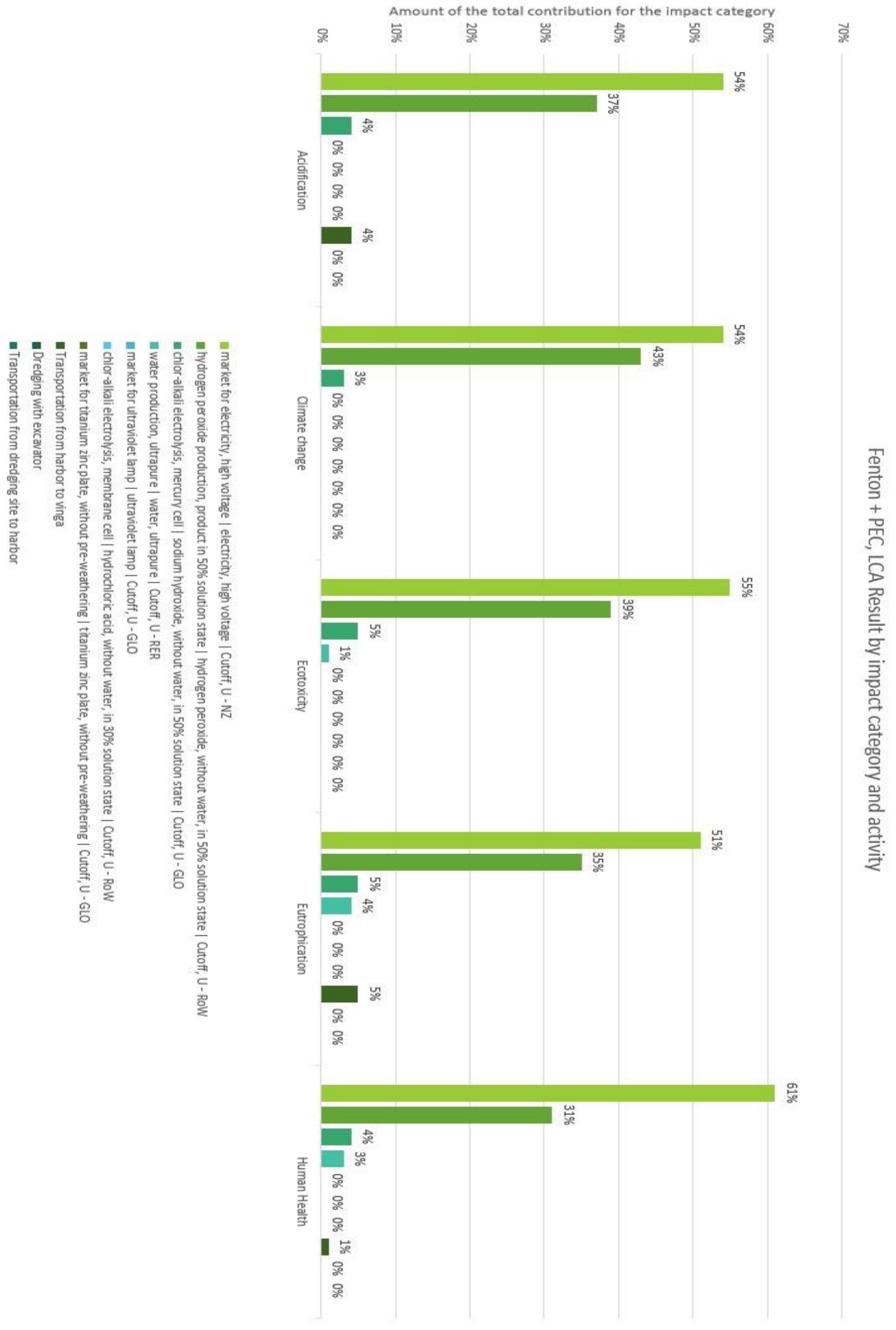


Figure 14: Impacts by the Fenton + PEC method. The figures explain the origin of the impacts that the LCA result showed. The results show the amount each activity contributes to the whole impact across each characterization category.

4.2.2 Methanol + Ultrapure Water + PEC

The method’s largest impact is as a source to Eutrophication, and the smallest regarding Climate Change. Across nearly all impact categories, methanol production stands for over half of the contribution to the impact, except for Climate Change, where sodium hydroxide (NaOH) production nearly equals methanol production in contribution. NaOH production stands overall as the second largest contributor to the impact, however with a smaller margin compared to the rest of the sources of impact (Figure 15).

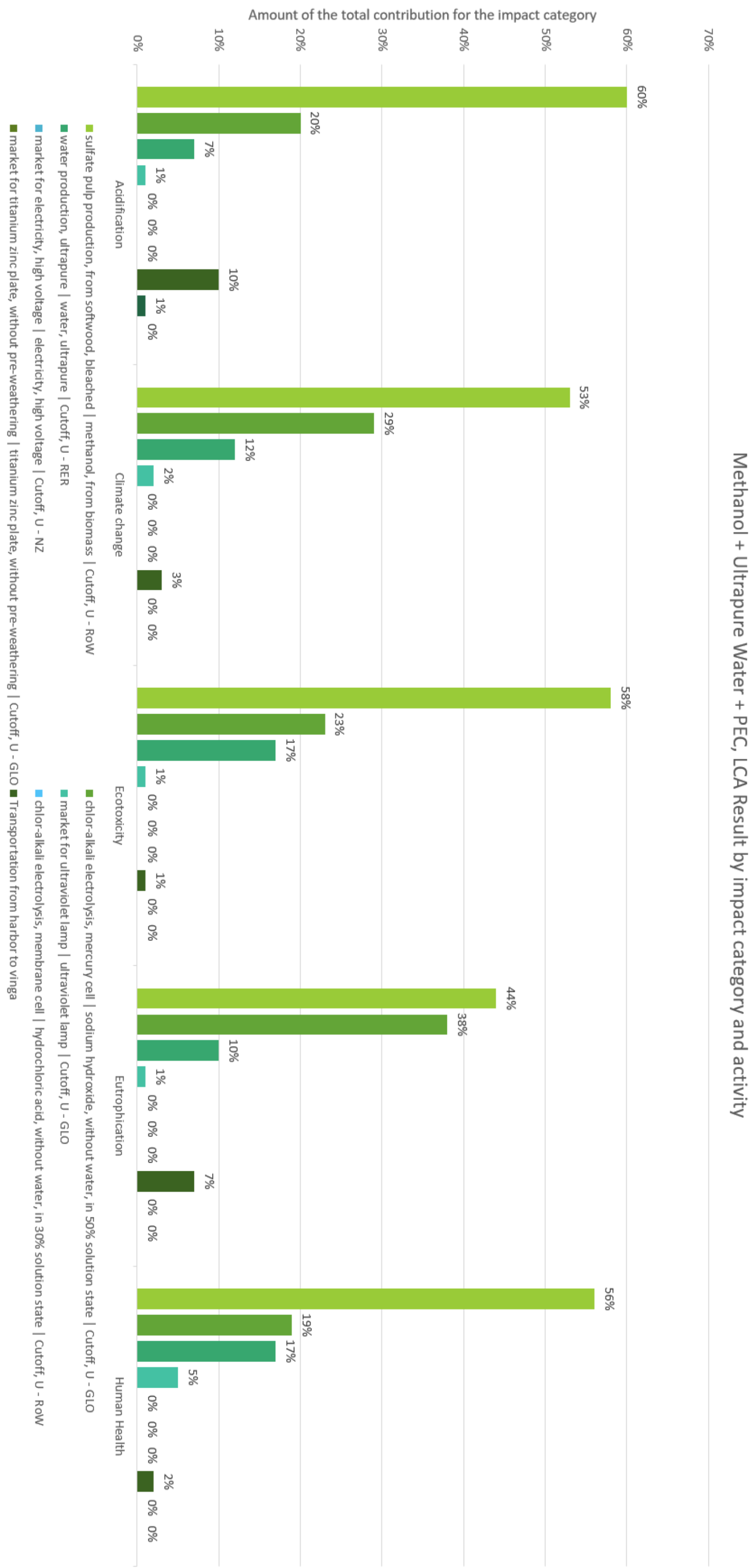


Figure 15: Impacts by the Methanol + Ultrapure Water + PEC method. The figures explain the origin of the impacts that the LCA result shows. The results show the amount each activity contributes to the whole impact across each characterization category.

4.2.3 Fenton at pH3

Based on the LCA results, the environmental impact of the Fenton at pH 3 treatment reveals contributions around all the different categories. The biggest impact is observed in the Climate change criteria, where 93% of the total impact is attributed to H_2O_2 production. Hydrogen peroxide plays a crucial role in the oxidation process and is something this treatment is dependent on. Acidification has 85% of the impact driven by H_2O_2 production. Going on to the Human Health impact, with 87% of the contribution also originating from H_2O_2 production, it shows that the health risks are connected to the production phase of this process. Ecotoxicity also sees an 87% contribution from chemical production, which indicates that the generation of H_2O_2 affects ecosystems. Eutrophication, which has lower impacts that still is notable, contributes to 76% from H_2O_2 production and 10% from chlor-alkali electrolysis for NaOH. The NaOH production is most noticeable in the categories Ecotoxicity, Eutrophication and Human Health. This also indicates that the Fenton process can contribute to nutrient buildup in water bodies, affecting the ecosystems. Water production has a really low impact on these criteria (Figure 16).

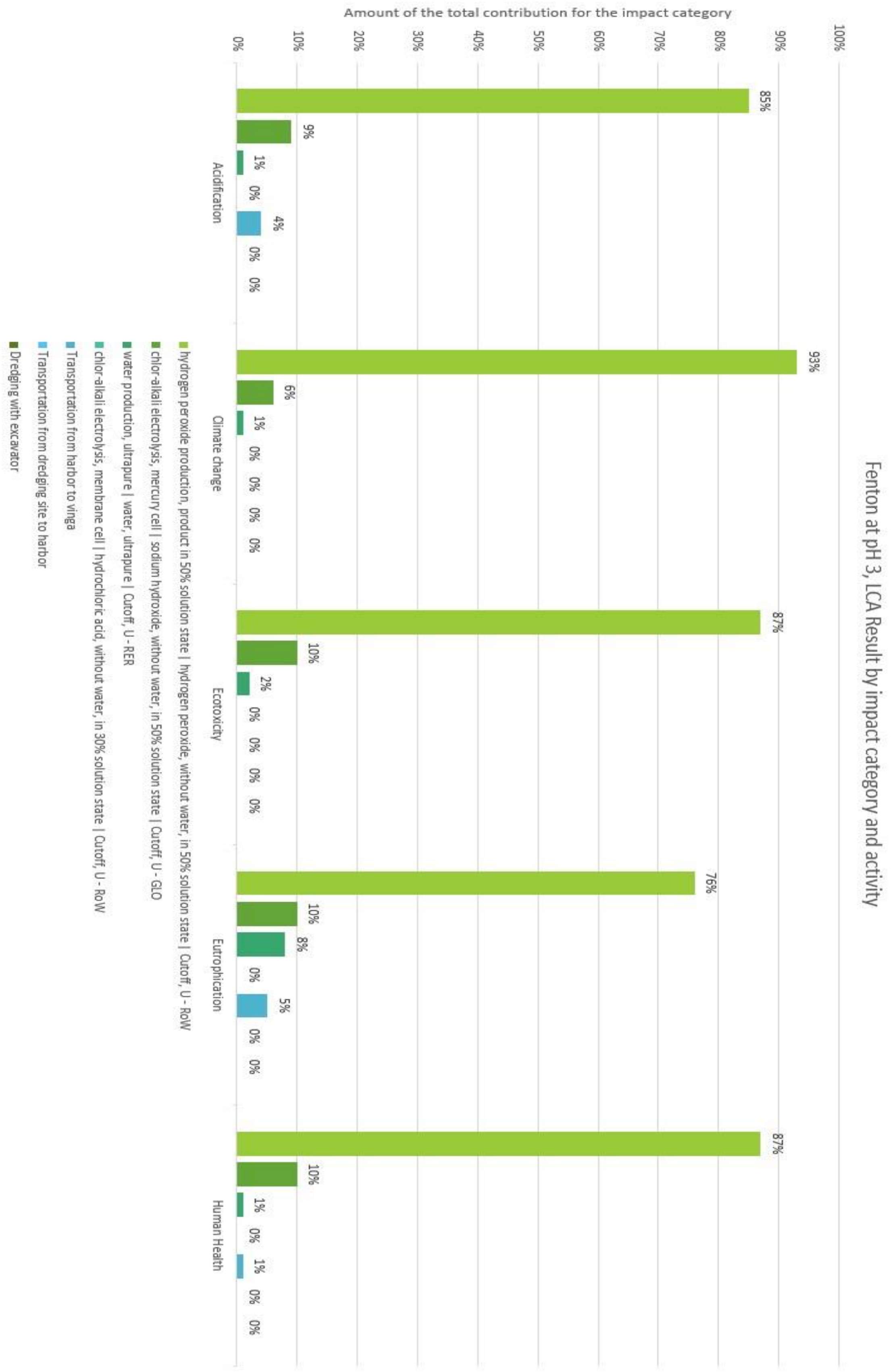


Figure 16: Impacts by the Fenton at pH3 method. The figures explain the origin of the impacts that the LCA result showed. The results show the amount each activity contributes to the whole impact across each characterization category.

4.2.4 Density Separation + PEC

For the Density Separation + PEC method, most of the environmental impact came from the market for salt category. While the highest ones are Ecotoxicity (86%) and Climate change (75%). Moreover, for the other categories, there were smaller percentages for the market for salt, but still it was the highest contribution for respective categories. Acidification contributes with 56%, Eutrophication with 62% and Human Health with 45% for the market for salt. The second largest contributors for the criteria were the transportation from the port to Vinga, those were highest for Acidification (37%) and for Eutrophication (32%). The smaller ones were for the rest; Climate change (15%), Ecotoxicity (6%) and Human Health (1%). Other contributors such as the market for electricity and ultraviolet lamps also impacted, but with a small percentage, that was not so noticeable as the market for salt and transportation of sediment.

Overall, salt usage dominates many of the environmental impacts, but other elements, like the UV lamps and transportation, also play significant roles in this method's environmental footprint. The method showed a more diversified environmental impact compared to the other treatment processes (Figure 17).

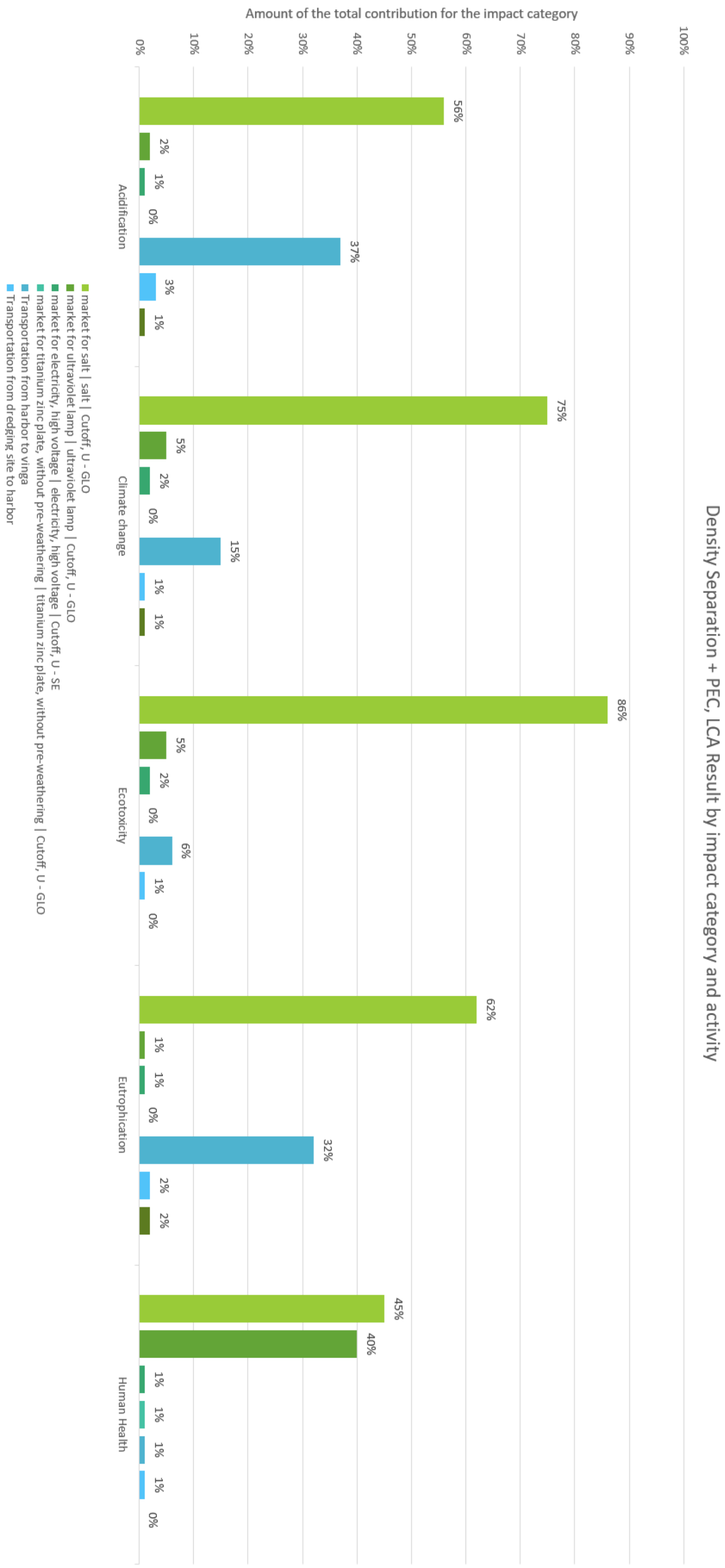


Figure 17: Impacts by the Density Separation + PEC method. The figures explain the origin of the impacts that the LCA result showed. The results show the amount each activity contributes to the whole impact across each characterization category.

4.3 MCDA Results based on workshop and survey

The results of the different steps of the MCDA, from initial gathering on opinion based on broad sampling using forms, detailed discussion and weight attribution and the final combination of weight and LCA results culminating in the complete MCDA.

4.3.1 Primary survey

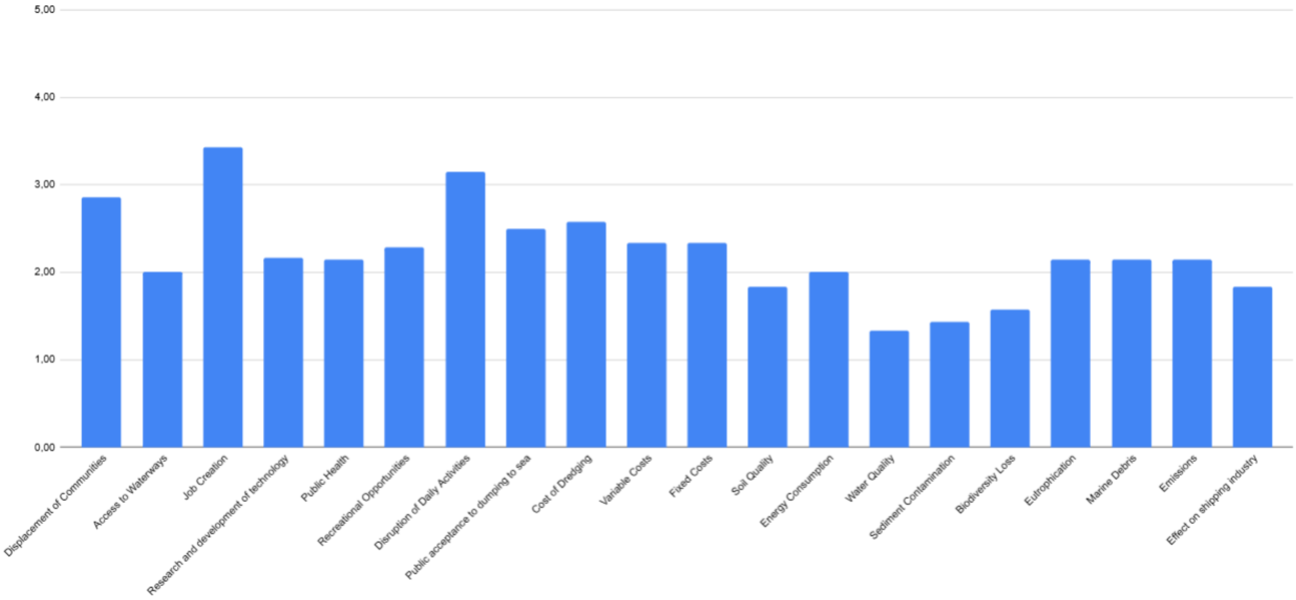


Figure 18: The result of the initial survey assessing the stakeholders’ preferences regarding the sustainability criteria, where 5 has the highest priority and 1 has the lowest priority.

The results of the initial forms published, with eight answers collected where the most important aspects identified are Greenhouse Gas Emissions (GHG), Sediment Contamination, Water Quality, Biodiversity Loss, Eutrophication and Public Health. These were in the later stages of the study renamed into Climate change, Acidification, Ecotoxicity, Human Health, Water Quality and Sediment Quality (Figure 18).

4.3.2 Result of workshop

The weighting of the aspects is the result of a workshop with six stakeholders: two representatives from Chalmers, one representative from a Swedish research institution, one representative of an environmental protection agency, one representative from a port owner and one representative from a geotechnical institution (Table 5). The stakeholders were asked to rate the importance of each criterion on a scale from 1 (unimportant) to 5 (very important). These ratings were then used to assign weights to each criterion, reflecting their relative importance in the decision-making process. The results of the workshop, the scorings of the various sustainability aspects, were transformed into percentages through a normal allocation of weight relative to the number of total points of preference given, with the result seen in Table 5.

Table 5: The weighting of each sustainability criteria based on the stakeholder's opinions from the workshop showed as a precentage.

Representatives	Climate Change	Eutrophication	Water Quality	Sediment Contamination	Human Health	Ecotoxicity
Academia	24%	10%	24%	19%	10%	14%
Environmental Protection Agency	20%	12%	16%	12%	20%	20%
Academia	20%	10%	15%	20%	10%	25%
Research Institute	17%	13%	17%	17%	13%	22%
Port Owner	9%	9%	23%	23%	18%	18%
Geotechnical Institution	21%	21%	26%	11%	11%	11%
Together	18%	9%	23%	23%	9%	18%

4.3.3 Result of the MCDA

The values for Climate Change, Eutrophication, Acidification, Human Health and Ecotoxicity come from the CLCA where a scoring of 100% was given a value of 1 and a scoring of 0% a 0, with a linear correlation. The values of Water Quality and Sediment Contamination come from the amount of removed TBT with a removal factor of 60% giving a value of 1, and a removal factor of 99% being given a 0, with an exponential correlation. The weighting criteria were determined by the stakeholder dialogue. The values for each individual method and each impact category were derived from the CLCA. The total scoring was calculated as the sum of the individual values ties their corresponding weighting criteria as seen in Table 6. A higher score signifies a higher relative impact of the method, and a lower scoring signifies a lower relative impact.

Table 6: The calculation table for the MCDA displays the values for the weighting, the LCA results, and the resulting weight adjusted impact.

Weighting	21%	11%	11%	26%	11%	21%	
Indicator	Climate Change	Eutrophication	Acidification	Sediment & Water Quality	Human Health	Ecotoxicity	Total
Density Separation + PEC	0.04	0.16	0.11	0.23	0.08	0.06	12%
Fenton + PEC	1	1	1	0.21	1	1	79%
Fenton at pH 3	0.93	0.99	0.97	0.82	0.74	0.98	90%
Methanol + Ultrapure Water + PEC	0.18	0.18	0,4	0.74	0.37	0.4	42%

The results of the MCDA are presented in Figure 19 where the higher the percentage, the higher the impact of the method, relative to the other methods, according to the MCDA. Fenton at pH3 has the highest relative impact, being at 90%, with Fenton + PEC being the second highest with 79%. Methanol + Ultrapure Water + PEC scores somewhat lower at 41%, and Density Separation + PEC is most sustainable at 12% (Figure 19).

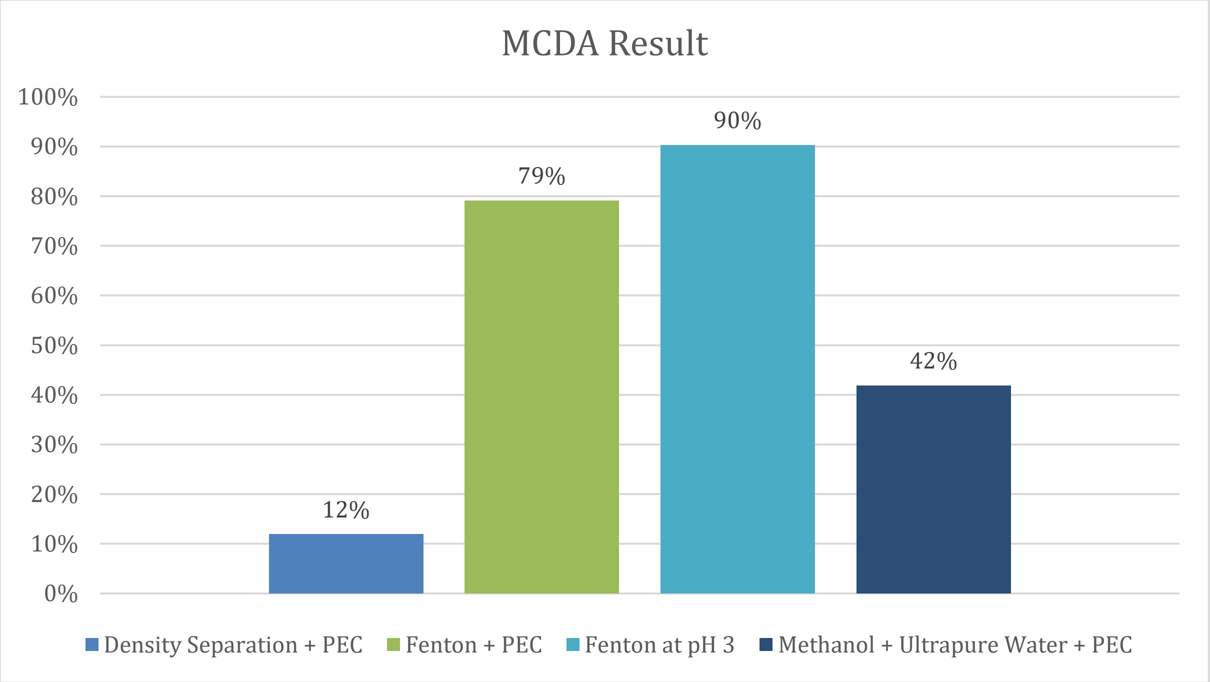


Figure 19: The impacts of the different sediment treatment methods as a result of the MCDA. Lower percentage means lower relative impact, higher percentage means higher relative impact of the treatment method.

4.3.4 Result of the MCDA, sensitivity adjusted

The results of the MCDA for the methods adjusted to the sensitivity analysis (Figure 20) where the higher the percentage, the higher the impact of the method, relative to the other methods. Fenton at pH3 has the highest relative impact, being higher than in the base scenario being 5% higher at 95%, with Fenton + PEC reducing the impact by 50%. Methanol + Ultrapure Water + PEC scores gain 4% at 45% and Density Separation + PEC is still the most sustainable at 11%.

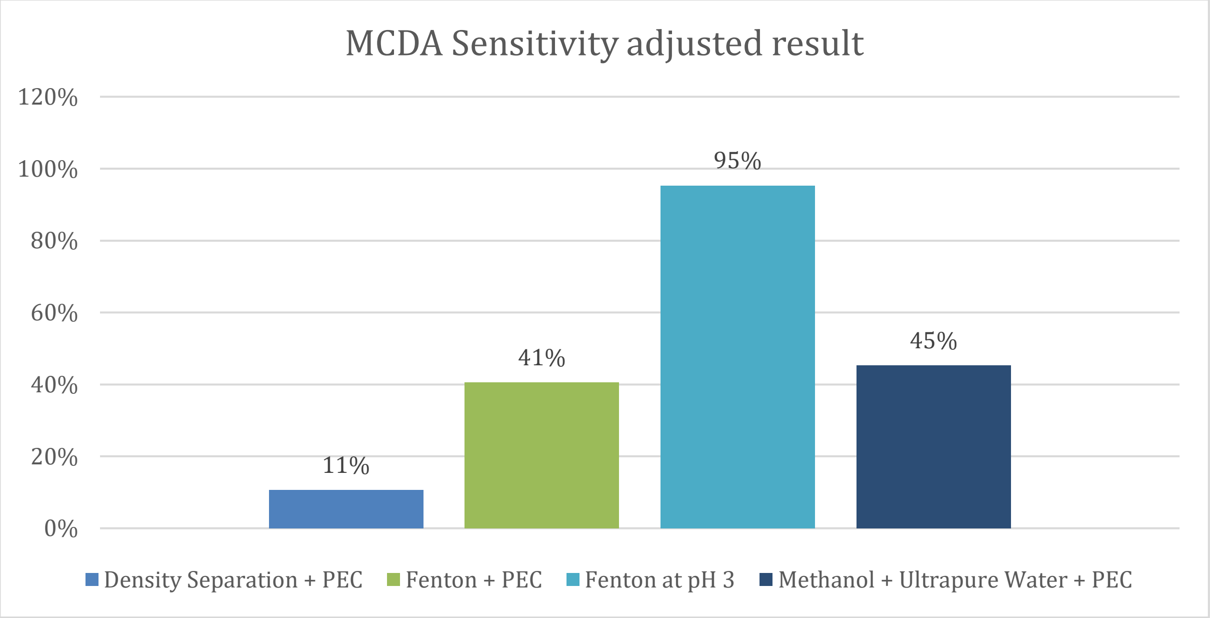


Figure 20: MCDA with values adjusted for 80% TBT reduction, with added sensitivity factors and changes. Lower percentage means lower relative impact, higher percentage means higher relative impact of the treatment method.

5. Discussion

In the discussion chapter the results are discussed in relation to what other researchers have found. It mentions what the findings mean and why they are important in a broader sense.

5.1 CLCA results

The results of the LCA, when the methods are adjusted for their effectiveness, show that Fenton + PEC has the highest negative environmental contribution across all impact categories. Fenton at pH3 follows though tightly after, with a negatable impact relative to Fenton + PEC, apart from the impact on Human Health, where it is considerably preferable. Methanol + Ultrapure Water + PEC is severely less impactful than the Fenton based processes across all impact categories, with more than 50% impact reduction regarding Acidification, Ecotoxicity and Human Health, and significantly less in the category of Climate Change. Density Separation + PEC has been proven to be the best method, across all impact categories (Figure 12).

While the adjusted results give a fairer comparison between the methods, there is much uncertainty of how the methods scale. For example, does a method with 90% removal of TBT remove 99% of the TBT in two cycles? If not, how much does the effect decrease with each cycle? This necessitates to also take into consideration the results of the methods without adjustments for efficiency, the only data that was collected by the institution, albeit only performed on lab scale. This unadjusted result (Figure 11) differs significantly from the results obtained from the lab, where no adjustment was made. Without the adjustment, Fenton + PEC has the greatest impact across all categories, while Fenton at pH 3 is lower and Methanol + Ultrapure Water + PEC and Density Separation + PEC is lowest.

Taking into consideration the uncertainty in the data of Ecoinvent, the adjustments in the sensitivity analysis showing the impacts of potential changes to the methods, these “best case scenarios” show again different results (Figure 13). Here Fenton at pH 3 has the highest impact across all categories, while Fenton + PEC and Methanol + Ultrapure Water + PEC obtain the second highest impact while Density Separation + PEC remains the least impactful method across all results. An interpreted mixture between the results of the CLCA, adjusted and not adjusted (Figure 11 & Figure 12) should, despite their fallacies, be seen as true for the current state of the methods, in the early stages of development and research, while the result for the sensitivity adjusted CLCA can be viewed as an indicator of what can be improved in future processes containing these methods.

5.1.1 Fenton + PEC

The results of the LCA indicate that Fenton + PEC is the least preferable option considering its sustainability, across all sustainability criteria. The main contributor to the impact across all categories is the electricity consumption of the method, for the photoelectrocatalysis. While electricity is detrimental to the method as the UVC-lamps need electrical energy for the photoelectrocatalysis to start (Norén et al., 2022), selection of electricity production is highly beneficial and can reduce a great amount of impact. Such change has the potential to reduce the impact of the method by nearly 50%. Using solar energy instead of electrical energy for the UVC-lamps and photoelectrocatalysis is a good option. The technology uses sunlight to activate the catalysis instead of electrical energy, which reduces the reliance on fossil fuels. By replacing electrical energy in the photoelectrocatalysis process, with solar power, gives environmental and economic sustainability. This optimizes resource utilization, fostering renewable energy associated with this treatment technology (Chen et al, 2021). Direct solar UV radiation can theoretically be feasible to activate the catalysis in the process for PEC. However, consideration on the limitation of sunlight and its intensity are dependent on weather conditions. The PEC system would have a bigger chance of working by just using solar energy to optimize efficiency. This approach gives a more reliably energy source than trying to capture natural UV light (Electrochemical Energy Lab, MIT, n.d.).

The second biggest impact is the production of hydrogen peroxide. As observed in the literature study, chemical manufacturing can have an energy-intensive process like hydrogen peroxide production. It is mainly due to the advanced oxidation processes (Norén et al., 2022; Wang & Wang, 2020). This highlights a potential improvement area, were replacing or even optimizing the production of H_2O_2 can be done to reduce emissions in this case. However, at this time it is hard to reduce the impact from the chemical, as no methods are currently available that would replace the chemical. All other contributors to the impacts accommodate less than 5% of the impact and should be considered not needed to change for the overseeing future, and optimizations such as switching to tap water is not needed, nor are the transportation costs comparatively close.

5.1.2 Methanol + Ultrapure Water + PEC

The result of the CLCA indicates that Methanol + Ultrapure Water + PEC is second to Density Separation + PEC in terms of sustainability, across all categories. Eutrophication, however, is the category where the method scores comparatively worst, and it is the method where there is no one clear single point of contribution towards the impact category, which is both the methanol production and the production of sodium hydroxide. The production of NaOH and its usage in the method only served the purpose increase the pH back to its original level (Norén et al., 2022). The production of NaOH stands for 19% (Human Health) to 38% (Eutrophication) of the contribution to the impact. Using the method without pH alteration of the salt, it would reduce the impact of the method by on average 30% across all impact categories. The greatest source of impact is the production of methanol from wood. While no direct alternatives were available in the database of Ecoinvent, alternative means to produce methanol exist such as green methanol which could potentially reduce the impact of the method by 50% to 60% thus reducing the total impact by 30% according to the sensitivity analysis (Chemical Safety Facts, 2022). The production of ultrapure water is also a significant contributor. Comparing the results of the sensitivity analysis (Figure 13) it is seen that the Eutrophication is reduced by 43% if the Water Quality is reduced from ultrapure water to tap water, as shown in Appendix B compared to Appendix C. Suggestively, it should be investigated if replacement of the water is possible without reducing the effect of the method, which can be the case, as the ultrapure water is used to not reintroduce new pollutants into the sediment (Tunç et al., 2021).

5.1.3 Fenton at pH 3

The environmental impacts of the Fenton treatment at pH 3 show hydrogen peroxide (H_2O_2) production being the most dominant contributor across the impact categories (Figure 16). Similarly, as observed in the discussion for Fenton + PEC this chemical is a potential improvement area, where replacing or even optimizing the production of H_2O_2 can be done to reduce emissions in this case.

The notable environmental load in this treatment is shown in Climate change (Figure 16). The LCA results show that H_2O_2 production drives nearly all the emissions related to this treatment method. Similar results were gained from Human Health and Ecotoxicity regarding H_2O_2 production. While the Fenton process is highly effective in removing organic pollutants such as TBT, the environmental tradeoffs need to be considered as well (Svensson et al., 2021; Norén et al., 2022). To mitigate this problem, one can look at the use of high-energy for chemical production. If renewable energy was used for chemical production instead of fossil energy that could be an improvement. This can result in improving the overall impacts of the process while still having an effective way of removing pollutants in sediment (Wang & Wang, 2020). As with different advanced oxidation processes, energy consumption is a large problem overall for the environmental impact (Liu et al., 2024). Exploring alternative oxidants may also help reduce the treatment's dependency on environmentally harmful chemicals like hydrogen peroxide and sodium hydroxide (Lin et al., 2023).

In addition to H_2O_2, sodium hydroxide (NaOH) production also had some contribution, albeit not as large as H_2O_2, but still contributed to Ecotoxicity and Eutrophication. This burden is gained through chlor-alkali electrolysis, which emits harmful by-products that can affect aquatic ecosystems (Kamei, 2023). To mitigate those emissions associated with NaOH, such as green production methods could benefit the environment. Another improvement area would be the transportation of sediment as the part also play a role in the overall sustainability for the different treatment methods (Pedersen et al., 2017).

To conclude, the Fenton at pH 3 treatment method require different approaches, while chemical production represents the most environmental burden, other factors such as transportation and energy usage cannot be overlooked. By targeting these impacts, the Fenton process can become more sustainable without lowering its effectiveness in pollutant removal in sediments.

5.1.4 Density Separation + PEC

In the Density Separation + PEC method, the results presented in Figure 17 indicate different environmental challenges. The impacts were largely attributed to the market for salt. In the beginning of the LCIA, laboratory grade sodium chloride was used according to the ingredients used in the laboratory trials (Pedersen et al., 2017). Sodium chloride production contributed a lot to the environmental impacts, thus the usage of food grade salt instead of laboratory grade salt was considered instead which halved the impact of the method. It was also seen that the salt had the largest contributor for this treatment method (Figure 17). The food grade salt was a more environmentally friendly alternative strengthening the argument that using less harmful alternatives in chemical production leads to improvement in sustainability (Svensson et al., 2021).

Another area for improvement was reducing resource consumption, particularly through closed-loop system that recycled the water used and materials. Such innovations can minimize waste and resource use, making the treatment method more sustainable and cost-effective (Svensson et al., 2021). This later results in a reduction in both environmental impacts and operational costs. Additionally, integrating the Fenton oxidation process after the Density

Separation + PEC for breaking down a wide variety of organic pollutants, can give a better result in lowering the organic pollutants in the sediment. It also can effectively reduce the additional treatment that will be required for this process. This helps address the methods limitations in treating complex organic pollutants (Lin et al., 2023; Norén et al., 2022).

Despite the method’s effectiveness, with a 90% removal rate of TBT, this method still faces some challenges related to the separation of pollutants and additional resource requirements. Optimizing resource use (for example the salt) and looking into recycling strategies could help reduce the Environmental and economic burdens associated with Density Separation + PEC. This results in a more evolved and sustainable solution for sediment treatment, benefiting both the ecosystems and Human Health in the long term (Duong et al., 2022; Pedersen et al., 2017).

5.2 MCDA results

The base scenario (Figure 19) shows that Fenton at pH 3 has the highest relative impact according to the MCDA, Methanol + Ultrapure Water + PEC is third with nearly half the impact and Density Separation + PEC is the most sustainable with one tenth of the impact of Fenton + PEC. It is important to note that this analysis consists of several biases and data limitations. With adjustments to the data through the sensitivity analysis in the LCA, the results become somewhat different, with Density Separation + PEC and Fenton at pH3 still being the best (former) and worst (latter) methods (Figure 19 & Figure 20).

Not all impact categories were assessed quantitatively, as sediment and Water Quality were assigned their values qualitatively. It was important to note that for TBT, there are clear regulations regarding the maximum allowed TBT content that the sediment must fulfil to be permitted to be deposited at the selected site outside of Vinga (Svea hovrätt Mark- och miljödomstolen, 2015) and thus the category cannot be equally assessed with the others, as it is a binary matter of either allowing the dumping or not[4]. The strictest regulations were derived from the Australian government's guidelines, which are not necessarily the same in Gothenburg but which the MCDA was based on (Australian Government Initiative, 2000). These two aspects should be taken into consideration while addressing the issues of choice of methods based on this MCDA as they can make the MCDA results shift, however, the final result of the LCA and the MCDA suggests that the conclusion that Density Separation + PEC is the most preferable option will not change.

5.3 Sources for errors

The stakeholder workshop and the survey which set the base for the MCDA had one main issue with the number of people who took part in the initial survey. The number of participants was small, and it is important for workshops like these to include a wider range of people. This leads to more different opinions and ideas. Without this, the decision-making may not fully reflect what the researchers are looking for (Sironen & Poikolainen, 2018). A more comprehensive approach is needed, the sensitivity analysis was conducted, but even with the analysis, certain perspectives from stakeholders could still be missing. A larger number of people conducting the survey and analysis would have strengthened the findings and helped

---

[4] Personal communication, representative of geotechnical institution, 22 August 2024.

ensure that the conclusions drawn reflected real-world concerns and needs (Glavič & Lukman, 2007).

So far, the methods presented have only been tested in a small-scale laboratory, with the data being taken from only lab scale. This means that some of the understanding of the treatments efficiency and challenges are at a small scale. It remains unclear how the processes behave when scaled up to industrial levels (Bates et al., 2023). While some treatment methods look promising in the lab, it is hard to say if they will give us the same results, when it comes to benefits and issues (Bates et al., 2023). When treatments like this begin to be applied to an industrial setting, uncertainties will be more, not only for building and upgrading the infrastructure, but also for fixing the problems that could arise under operation (Svensson et al., 2021). The questions that would arise then are whether these methods, that have all these uncertainties and possible extra costs, are worth developing and working with. One will consider "Method 0 - No Treatment" a more representative choice for this approach. The developers and working staff would have to find a balance with these unknown risks and costs, to continue with their decision making (Andreottola et al., 2010). For mitigating high costs for building the facilities for dredged sediment, one needs to consider the money that is going to spend on the building and the ongoing costs to operate it. Building a big facility that can uphold tons of dredged sediment at Scandiaporten (Gothenburg) would require much money. The costs would be due to technology, infrastructure, and training for staff. However, over time, the facility could save money by making processes more efficient and possibly reducing costs related to environmental cleanup (Svensson et al. 2021). In the workshop discussions, a port representative pointed out that even though the facility costs might be expensive, the long-term financial benefits could make it worth the investment. One needs to make sure to do this in a sustainable way for gaining those benefits (Wang & Wang 2020). For treatments like Fenton processes, the facility would need equipment to handle hazardous chemicals like H_2O_2 and pH adjusters such as HCl and NaOH, which adds to the cost as well. While simpler treatment methods like Density Separation + PEC might cost less, since one uses less chemicals and is more dependent on mechanical equipment. But still, it is important to compare these costs with these different treatment methods or disposal methods to see if it is feasible economically (Lin et al., 2023; Andreottola et al. 2010). Only relying solely on theoretical models can lead to underestimating environmental impacts when applied on a larger scale (Bates et al., 2023; Tillman n.d.).

The data available in the database Ecoinvent included much of the data needed, but at times proxies had to be made, changing geographical data on the input of the processes as regional or national data for Sweden was not available. This can lead towards a slight bias towards the methods relying heavily on chemicals to be somewhat misrepresented and shown as having a higher impact than they have. However, as shown in the sensitivity analysis (Figure 20) this should not affect significantly the values of results of which methods are to be preferred.

5.4 Further study recommendations and considerations

The aim of the study was to investigate which methods for treating dredged sediment are the most sustainable. However, in doing so more questions were posed that are worth looking into and potential research projects would enhance the results of this study. The major uncertainties in this study are caused by uncertainties in data, deriving from either lack of regional data or data based on lab results. To get the real-life data a project a pilot project is suggested to be conducted where Density Separation + PEC can be used for treatment of the dredged sediment, where the impact can be assessed and compared to these theoretical results.

This study shows the relative impact of each subprocess in the process of treating the dredged sediment. These results should be investigated, and further recommendations may be made on how to optimize the process, by changing parts of the process or removing parts of the process completely, in order to improve (lower) the impact of the methods further. In the first iterations of the inventory assessment, pure NaCl powder was used for the process, in the Density Separation + PEC method. The original results of the study indicated that Density Separation + PEC might be the most impactful method of cleaning the dredged sediment. However, after altering the source of salt to regular table salt, produced through desalination of water or mining, the result shows that Density Separation + PEC is the most sustainable alternative. This leads to the opportunity that there may be other chemicals that can be altered or entirely replaced and for that purpose professional chemists could be invited to investigate further inefficiencies in the methods.

Photoelectrocatalysis requires light energy, and this causes great dependency on the upstream source of energy. Investigation on supplying the energy need of facilities that treat dredged sediment could be made, with focus on creating energy supplies with offshore wind power, as all major harbors lie by the sea. Furthermore, perhaps direct UV from the sun could be utilized in the treatment of TBT, instead of the usage of UV lamps (Electrochemical Energy Lab, MIT, n.d.). While UV from the sun is generally weaker than from UV lamps (which are closer), perhaps a system of amplifying the intensity of the sunlight (using mirrors and lenses) could be used to achieve similar effects.

5.4.1 Harm to Nature and Biodiversity Loss

A government representative from the workshop discussed how Biodiversity has experienced losses since the 1960s and 1980s, due to TBT pollution. The environmental harm due to widely used TBT leads to the degradation of marine ecosystems (Antizar-Ladislao, 2008). The workshop representative discussed that it is crucial to avoid further damage to the natural environment and to address these ongoing challenges with effective solutions (Wang et al., 2023).

The representative had been working with TBT for a long time, he also addressed that while ignoring the harm that has already been done is not an option, one must be cautious about increasing pollution levels even further. Raising contamination limits will not be an acceptable approach, as additional harm should be prevented (Antizar-Ladislao, 2008). If the current methods for treating contaminated sediment can mitigate these issues, then the results that will be gained will be considered sustainable (Antizar-Ladislao, 2008). The message here would be to consider these treatment methods also from a biodiversity perspective.

When judging treatment methods, it is important to also see the effectiveness they give and the possibility of causing more harm to the environment (Wang et al., 2023). As highlighted in previous discussions, the goal is not only to manage current pollution levels but also to ensure that no more creation of further risks to the ecosystems and biodiversity is gained (Svensson et al., 2021; Wang & Wang, 2020). As new technologies are developed and implemented, people must be mindful of their further impacts on the environment to prevent further losses, this will give us a sustainable future with these new technologies (Wang et al., 2023).

5.4.2 Port of Gothenburg and Scandiaporten

Dredging activity in the port of Gothenburg produces every five years 100.000-ton sediment which is not suited for dep sea disposal, without prior treatment. With the upcoming project Scandiaporten, an additional 200.000 to 300.000 ton would require treatment. The amount of environmental impact as calculated with the values in appendix B, times 100000 and 300000 respectively is presented in Table 7. For reference, comparing the results of Density Separation + PEC and Fenton at pH3, 1,700 kg CO_2-eq is comparable to the emissions from producing 400 smartphones, while 200,000 kg CO_2-eq equals the annual carbon footprint of a medium-sized manufacturing facility. Acidification impacts, like 25 mol H^+ eq, correspond to the production of 1 kg of ammonia fertilizer, whereas eutrophication impacts, such as 140 kg N-eq, compare to nitrogen runoff from applying 200 kg of fertilizer. For human health damage, 0.006 DALYs is comparable to smoking 30-40 cigarettes, and 679,188 CTUe in ecotoxicity aligns with the toxic impact of 50 kg of pesticides released into aquatic systems. (Directorate-General for Environment, n.d).

Table 7: Calculated impact for the dredging in the port of Gothenburg and the Scandiaporten project, based on the results of the LCA.

	Acidification [mol H^+-Eq]	Climate Change [ton CO_2-Eq]	Eco-toxicity [CTUe]	Eutrophication [kg N-Eq]	Human Health [DALYs]
Maintenance dredging 100 kton/5 years					
Methanol + Ultrapure Water + PEC	146	18 007	135 531	56	0.026
Fenton + PEC	308	93 634	304 278	68	0.048
Fenton pH3	465	203 43	679 188	140	0.136
Density Separation + PEC	25	1 735	5 346	6	0.006
Scandiaporten dredging 300 kton					
Methanol + Ultrapure Water + PEC	439	54 02	406 594	169	0.079
Fenton + PEC	924	280 901	912 834	203	0.144
Fenton pH3	1.394	610 291	2 037 565	421	0.407
Density Separation + PEC	75	5 204	16 038	18	0.017

Additional issues to take into consideration in the case of the dredging in the port and during the project are the following: The new treatment method needs to have good logistical management that works effectively. A representative of the geotechnical institution pointed out at the workshop that when planning to use these treatment methods, one should think about getting the right required regulatory approvals to ensure feasibility for continued development. The representative also mentioned that it is important to install the necessary equipment, training staff and optimizing the processes (Svensson et al. 2021). The feasibility for the project, Scandiaporten, is dependent on having the right trained workforce and the best for the environment would be having the facility close to the dredging site. An academia representative highlighted the importance of always evaluating the processes to make sure it stays workable within the timeline of these kinds of projects (Svensson et al. 2021). Methods like Density Separation + PEC take longer to execute but are easy to manage. Compared to the timing for treatment methods like Fenton's for large projects can be challenging. These kinds of methods work quickly, but need precise monitoring and control, which can be tricky on larger scales. The key here would be to find a balance between speed and practicality (Norén et al. 2022).

5.4.3 Local impact vs global impact

If one looks at the impacts locally, treating dredged sediment can lead to lower pollution risks, cleaner water and better access ways in water for marine life that results in healthier ecosystems (Bates et al., 2023). Another academia representative mentioned in the workshop that improvements, in water bodies, could boost public health and offer more opportunities. Globally, cutting down on greenhouse gas emissions from sediment treatment might seem small, compared to the GHG emissions gained from other sources, but can be affected worldwide and help combat Climate Change (Svensson et al. 2021; Bates et al., 2023). Proper management locally can have global benefits by reducing long-term impacts.

If these sediment treatment methods prove themself to be successful, they would be a huge help for reducing harmful organic pollutants such as TBT in marine ecosystems worldwide (Pedersen et al. 2017: Bates et al., 2023). The methods may even be used to recycling and re-use toxic metals that are in these water bodies. Using treatment methods in different industries and regions could lower pollution in oceans, which would prevent harmful substances from accumulating, also improving food chains and the services ecosystems provide. Globally this would benefit public health and communities that are dependent on fishing (Tunç et al. 2021).

5.4.4 Dredging of areas with high contamination

The study focused on assessing the treatment methods based a scenario of the usual concentration of TBT across the port of Gothenburg. However, dredging that would be done in location with higher contamination, such as 750µg/L (Magnusson, 2020) would require substantially higher amounts of “cycles” of treatment with at least seven additional cycles for Density Separation + PEC and Fenton at pH3, increasing the impact of these methods sevenfold is a linear removal rate is assumed (Table 3). Highly contaminated sediment could perhaps be treated differently, instead of treating the most polluted sediment, perhaps such sediment could be disposed of at landfills or displaced more carefully into the deep sea, and then covered by layers of treated sediment, so that the toxic waste would be buried and unable to sipper out. However, weather such “burial” of TBT contained sediment would be an effective way of preventing the TBT from contaminating the water should be investigated by a further study as this theoretical study cannot answer such speculation.

6. Conclusion

In this chapter the key findings of the study provide us with a summary of the results and importance of the research. It also includes recommendations for future research and applications.

6.1 Conclusion of results

The thesis evaluated the environmental and sustainability impacts of the chosen sediment treatment methods. The study used a Comparative Life Cycle Assessment (CLCA) and Multi-Criteria Decision Analysis (MCDA) to reach the goal of the study. The results showed that Density Separation + PEC is the most sustainable option. Fenton + PEC showed the highest environmental burden, due to the dependance on electricity and hydrogen peroxide. The MCDA results also showed Density Separation + PEC as the most sustainable treatment method with a minimal impact compared to the other treatment methods. Methanol + Ultrapure Water + PEC and Fenton at pH3 showed high environmental impacts related to energy and chemical usage/production. The sensitivity analysis showed some reduction in impact that could be achieved by changing the energy source for the treatment methods, water source and transportation methods. With this change, Density Separation + PEC is still the most viable for sustainable sediment treatment.

6.2 Recommendations for future research

Future research should focus on scaling up the treatment methods to gain knowledge about real-world viability. Fenton processes, which may give different environmental and operational loads at larger scales, should be considered and examined when scaled up. Putting these treatment methods in practice fields would help validate LCA findings and address the different challenges that may occur, such as cost-efficiency and safety in industrial applications. Further research on alternative oxidants or renewable energy in the Fenton process, could reduce environmental impacts. Also, by expanding the stakeholder engagement in MCDA assessments is important to gain a broader perspective and better considerations connected to societal and economic considerations. An aspect that was not covered in this study, but which was highlighted by stakeholders throughout the research phase is that a closed loop systems within the different methods could enhance resource efficiency, minimizing chemical inputs, water use and recycling of heavy metals and should be investigated further.

References

1. Al-Hussein, A. S. A. (2021). *Using sulfuric acid (H_2SO_4) for pH adjustment in water treatment*. Basrah Oil Company. 53f559ff8ea8fef7 (iasj.net)
2. Andreottola, G., Bonomo, L., De Gioannis, G., Ferrarese, E., Muntoni, A., Polettini, A., Pomi, R., & Saponaro, S. (2010*). Lab-scale feasibility tests for sediment treatment using different physico-chemical techniques*. Retrieved from Lab-scale feasibility tests for sediment treatment using different physico-chemical techniques | Journal of Soils and Sediments (springer.com)
3. Antizar-Ladislao, B., (2008). *Environmental levels, toxicity and human exposure to tributyltin (TBT)-contaminated marine environment: A review.* Retrieved from Environmental levels, toxicity and human exposure to tributyltin (TBT)-contaminated marine environment. A review - ScienceDirect
4. Arora, P. (2017). *Physical, chemical and biological characteristics of water (e Content Module)*. Retrieved from Physical, Chemical and Biological Characteristics of Water (e Content Module) (researchgate.net)
5. Australian Government Initiative, (2000), *Tributyltin (TBT) in freshwater and marine water.* Retrieved from Tributyltin (TBT) in freshwater and marine water
6. Bashyal, J. (2023, July 14). *Sodium hydroxide (NaOH): Formula, properties, preparation, uses*. Chemistry Page. Retrieved from Sodium Hydroxide (NaOH): Formula, Properties, Preparation, Uses (scienceinfo.com)
7. Bates, M. E., Fox-Lent, C., Seymour, L., Wender, B. A., & Linkov, I. (2023). *Life cycle assessment for dredged sediment placement strategies*. Retrieved from Life cycle assessment for dredged sediment placement strategies - ScienceDirect
8. Baumann, H., & Tillman, A.-M. (2004). The hitch hiker's guide to LCA: An orientation in life cycle assessment methodology and practice.
9. Bruce, P., Bradshaw, C., Ohlsson, Y., Sobek, A., Christierson, A. (2021). Inconsistencies in how environmental risk is evaluated in Sweden for dumping dredged sediment at sea.
Frontiers in Marine Science, 8. Retrieved from https://doi.org/10.3389/fmars.2021.755443
10. Canadian Center for Occupational Health and Hazard, (2024), *What is a LD_{50} and LC_{50}?*
CCOHS: What is a LD_{50} and LC_{50}? Retrieved from: https://www.ccohs.ca/oshanswers/chemicals/ld50.html
11. CDC Foundation. (n.d.). *What is public health?* Retrieved from https://www.cdcfoundation.org/what-public-health
12. Chemical Safety Facts. (2022). *Methanol*. Retrieved from https://www.chemicalsafetyfacts.org/chemicals/methanol/
13. Chen, P., Zhang, Y., Zhou, Y., & Dong, F. (2021). *Photoelectrocatalytic carbon dioxide reduction: Fundamental, advances, and challenges.* Nano Materials Science, *3*(4), 344–367. Retrieved from Photoelectrocatalytic carbon dioxide reduction: Fundamental, advances and challenges - ScienceDirect

14. CIRAIG, (2022), *About CIRAIG* Retrieved from: About CIRAIG - CIRAIG

15. Commission of the European communities, (2009), EU *Regulation (EC) No 782/2003 and Directive 89/677/EEC* Retrieved from: https://ec.europa.eu/smartregulation/impact/ia_carried_out/docs/ia_2009/sec_2009_0705_2_en.pdf

16. Department for Communities and Local Government. (2009). *Multi-criteria analysis: a manual*. London: Department for Communities and Local Government. Retrieved from https://eprints.lse.ac.uk/12761/1/Multi-criteria_Analysis.pdf

17. Directorate-General for Environment, (n.d), *Life Cycle Assessment & the EF methods: Comprehensive coverage of impacts* Retrieved from: https://greenbusiness.ec.europa.eu/environmental-footprint-methods/life-cycle-assessment-ef-methods_en

18. Duong, T. T., Le, P. T., Nguyen, T. N. H., Hoang, T. Q., Ngo, H. M., Doan, Tran, T. K. C., Ho, T. C., Phuong, N. N., & Strady, E. (2022). *Selection of a Density Separation solution to study microplastics in tropical riverine sediment.* Retrieved from https://pubmed.ncbi.nlm.nih.gov/34993616/

19. Ecoinvent, (2024), *ecoinvent v3.10 Cutoff Unit Processes, ecoinvent association*. Retrieved from https://ecoinvent.org

20. Electrochemical Energy Lab, MIT, (n.d.), *Photoelectrocatalysis concept*. Retrieved from https://web.mit.edu/~eel/pechem.html#:~:text=Photoelectrocatalysis%20Concept%20One%20of%20the%20major%20roadblocks%20to,including%20hydrogen%20and%20simple%20hy drocarbons%20such%20as%20methanol

21. Encyclopaedia Britannica, (2024). *Biodiversity loss*, Retrieved from Biodiversity loss | Causes, Effects, & Facts | Britannica

22. European Platform on LCA. (2022). Environmental Footprint reference package 3.1
(transition phase). Retrieved from European Platform on LCA

23. Glavič, P., & Lukman, R., (2007*), Review of sustainability terms and their definitions.* Journal of Cleaner Production, *15*(18), 1878-1890. https://doi.org/10.1016/j.jclepro.2006.12.002

24. Göteborgs Hamn, (2017), *Om Göteborgs Hamn*, Retrieved from https://web.archive.org/web/20170804121900/https:/www.goteborgshamn.se/omhttps://web.archive.org/web/20170804121900/https:/www.goteborgshamn.se/om-hamnen/omgoteborgshamn/hamnen/omgoteborgshamn/

25. James, D. (12 July 2012). *Ecotoxicology – NOEC and LOEC*. Quantics Biostatistics. Retrieved from https://www.quantics.co.uk/blog/ecotoxicology-noec-and-loec/

26. Liu J. et al, (9 May 2024), Photoelectrocatalysis/photoelectro-fenton system based on conelike TiO2/nickel foam photoanode for efficient degradation of carbamazepine: Comparison with DSA. Retrieved from https://www.sciencedirect.com/science/article/pii/S1385894724035757

27. Johansson E., (2016) Zero Eutrophication, Retrieved from Zero Eutrophication - Swedish Agency for Marine and Water Management

28. Knapp, S. (2020, October 27). *Hydrochloric acid.* Biology Dictionary. Retrieved from https://biologydictionary.net/hydrochloric-acid/

29. Pedersen K. B. et al, (29 April 2017), *Simultaneous electrodialytic removal of PAH, PCB, TBT and heavy metals from sediments* Retrieved from https://www.sciencedirect.com/science/article/pii/S0301479717304231

30. LibreOne. (n.d.). Polar protic and aprotic solvents. In *Organic chemistry supplemental modules*. Retrieved from Polar Protic and Aprotic Solvents - Chemistry LibreTexts

31. Lin Y., Qiao J., Sun Y., & Dong H., (2023). *The profound review of Fenton process: What's the next step?* Journal of Environmental Sciences. Retrieved from https://doi.org/10.1016/j.jes.2023.10.005

32. Magnusson, M., & Bergkvist, J., (2020), Miljöförvaltningen Göteborgs Stad, R2021:07 Effekter av tennorganiska föreningar En undersökning i sju småbåtshamnar i Göteborg 2020
Retrieved from https://goteborg.se/wps/wcm/connect/4c26e6a7-69a6-4531-afdf-3026ba4342f9/N800_R_2021_07+Effekter+av+tennorganiska+f%C3%B6reningar.pdf?MOD =AJPERES

33. Kamei M., (2023), *Treatment of polluted sediment through sediment washing and Photoelectrocatalysis* Retrieved from https://odr.chalmers.se/items/7342c04d-df67-4c53a99b-fa56723a845d

34. Ministry of Climate and Enterprise, (11 March 2021), *Sweden's climate policy framework.*
Government of Sweden. Retrieved from Sweden's climate policy framework - Government.se

35. Svensson N., Anna N., Strömvall A.M., et al, (27 November 2021), *Integrated cost and environmental impact assessment of management options for dredged sediment* Retrieved from https://doi.org/10.1016/j.wasman.2021.11.031

36. Norén A., Lointier C., Modin O. et al, (2022=, *Removal of organotin compounds and metals from Swedish marine sediment using Fenton's reagent and electrochemical treatment* Retrieved from https://research.chalmers.se/publication/528135/file/528135_Fulltext.pdf

37. Owsianiak M., Hauschild M. Z., Posthuma L., Saouter, E., Vijver M. G. Backhaus T., Douziech, M., Schlekat, T., & Fantke, P. (2022). *Ecotoxicity characterization of chemicals:*
Global recommendations and implementation in USEtox. Environment International, 164,
107192. Retrieved from https://www.sciencedirect.com/science/article/pii/S0045653522033008

38. Pedersen, K. B., Lejon, T., Jensen, P. E., & Ottosen, L. M. (2017). *Simultaneous electrodialytic removal of PAH, PCB, TBT and heavy metals from sediments.* Journal

of Environmental Management, 197, 1-9. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0301479717304231

39. Public Health Notes, (n.d.), *Disability-adjusted life years (DALY).* Retrieved from https://www.publichealthnotes.com/daly-disability-adjusted-life-years/

40. Roger Williams University, (n.d.)., *Introduction to Oceanography. 5.5 Dissolved gases: Carbon dioxide, pH, and ocean acidification.* Pressbooks. Retrieved from https://rwu.pressbooks.pub/webboceanography/chapter/5-5-dissolved-gases-carbondioxide-ph-and-ocean-acidification/#:~:text=If%20pH%20rises%20%28low%20%5BH%20%2B%20%5D%29%2C%20 bicarbonate,remove%20H%20%2B%20ions%20and%20raise%20the%20pH.

41. Sekizawa J., Suter G., Birnbaum L., (2003), *Integrated Human and Ecological Risk Assessment: A Case Study of Tributyltin and Triphenyltin Compounds Integrated Human and Ecological Risk Assessment: A Case Study of Tributyltin and Triphenyltin Compounds* Retrieved from: https://www.tandfonline.com/doi/abs/10.1080/718990536

42. Sironen, S. M., & Poikolainen, L. (2018). Spatially referenced decision analysis of long-term forest management scenarios in southwestern Finland. Journal of Forest Economics, 20(4), 1850009. Retrieved from Spatially Referenced Decision Analysis of Long-Term Forest Management Scenarios in Southwestern Finland (researchgate.net)

43. Olushola S. Ayanda, Olalekan S. Fatoki, Folahan A. Adekola, & Bhekumusa J. Ximba, (16 May 2012), *Fate and Remediation of Organotin Compounds in Seawaters* and Soils Retrieved from https://digitalknowledge.cput.ac.za/bitstream/11189/3640/1/Ayanda_OS_Fatoki_OS_ Adekola _FA_Ximba_BJ_AppSci_2012.pdf

44. Svea hovrätt Mark- och miljödomstolen. (2015). *Mål nr M1260-14*. Retrieved from https://www.domstol.se/mark--och-miljooverdomstolen/mark--och-miljooverdomstolensavgoranden/2015/73378/

45. Swedish Environmental Protection Agency. (2024). *Contaminated sediments*. Retrieved from Contaminated sediments (naturvardsverket.se)

46. Tillman, A.-M. (n.d.). *Environmental systems analysis* [Course material]. Chalmers University of Technology.

47. Tunç M., Ay Ü., Can S. Z., Bingöl D., & Ün İ. (2021). Quantification of tributyltin in seawater using triple isotope dilution gas chromatography–inductively coupled plasma mass spectrometry achieving high accuracy and complying with European Water Framework Directive limits. Retrieved from Quantification of tributyltin in seawater using triple isotope dilution gas chromatography–inductively coupled plasma mass spectrometry achieving high accuracy and complying with European Water Framework Directive limits - ScienceDirect

48. U.S. Environmental Protection Agency. (2023). *Superfund: Contaminated sediments*. Retrieved from Superfund: Contaminated Sediments | US EPA

49. Wang, J., & Wang, S. (2020). Reactive species in advanced oxidation processes: Formation, identification, and reaction mechanism. Chemical Engineering Journal, 401, 126033.

Retrieved from Reactive species in advanced oxidation processes: Formation, identification and reaction mechanism - ScienceDirect

50. Wang, Z., Wang, T., Zhang, X., Wang, J., Wu, Q., Nepovimova, E., Watson, A. E., & Kuca, K., (2023). *Biodiversity conservation in the context of climate change: Facing challenges and management strategies.* Retrieved from Biodiversity conservation in the context of climate change: Facing challenges and management strategies - ScienceDirect

51. USEtox Team. (n.d.). *What are the units of characterization factors in USEtox* Retrieved from https://usetox.org/faq-page/how-use-usetox-characterization-factors/what-are-unitscharacterization-factors-usetox

52. World Health Organization. (n.d.). *Disability-adjusted life years (DALYs).* The Global Health Observatory. Retrieved from Disability-adjusted life years (DALYs) (who.int)

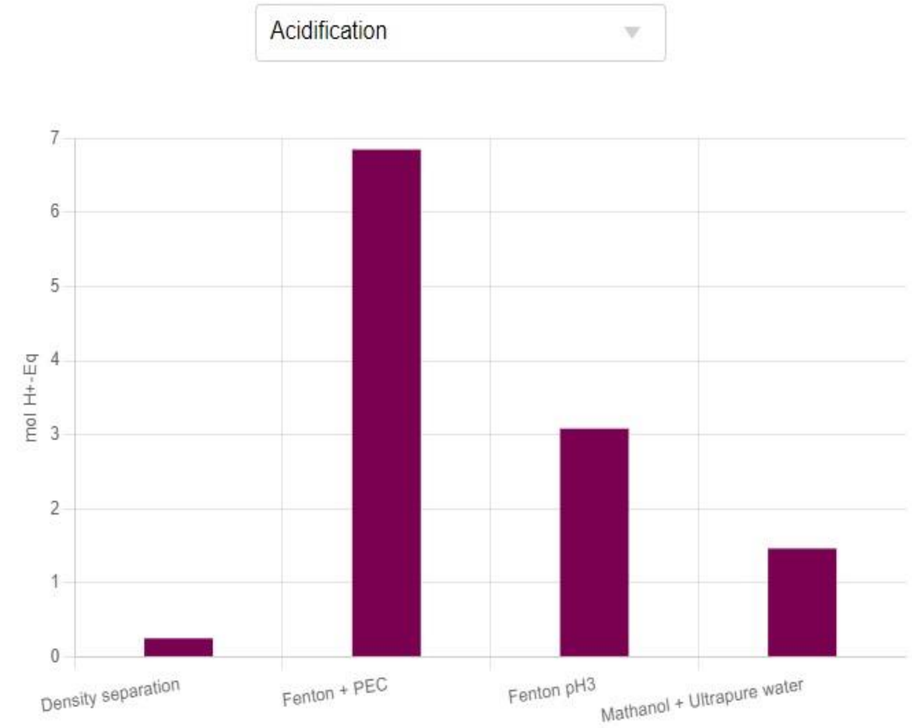
53. Yale University Library. (n.d.). *Steps in conducting a literature review*. Yale University Library Research Guides. Retrieved October 7, 2024, Retrieved from https://guides.library.yale.edu/c.php?g=296242&p=1973764

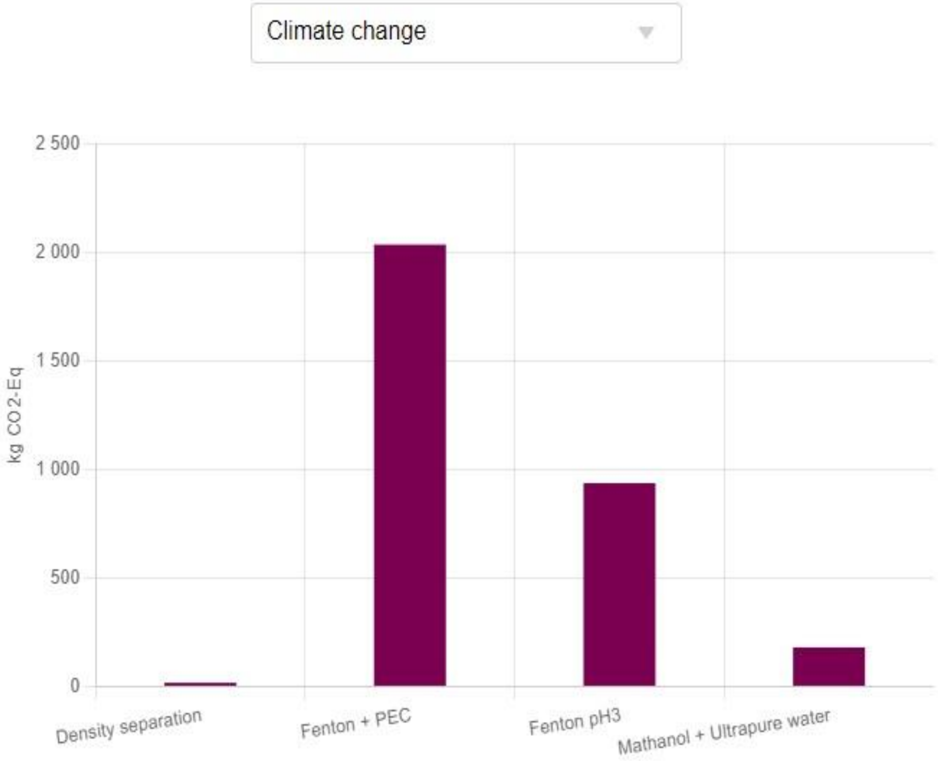
54. Zhang, M.-H., Dong, H., Zhao, L., Wang, D.-X., & Meng, D. (2019). A review on Fenton process for organic wastewater treatment based on optimization perspective. *Science of the Total Environment*, *670*, 110–121. Retrieved from: https://doi.org/10.1016/j.scitotenv.2019.03.180

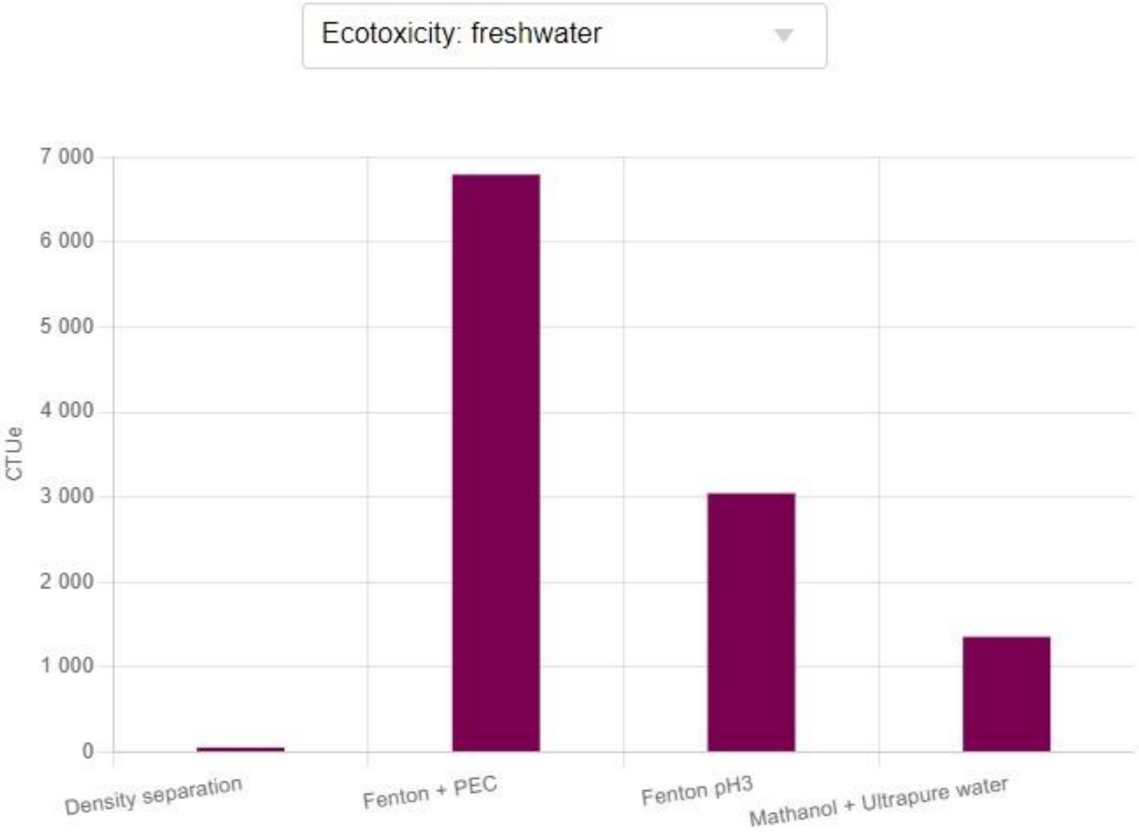
Appendixes

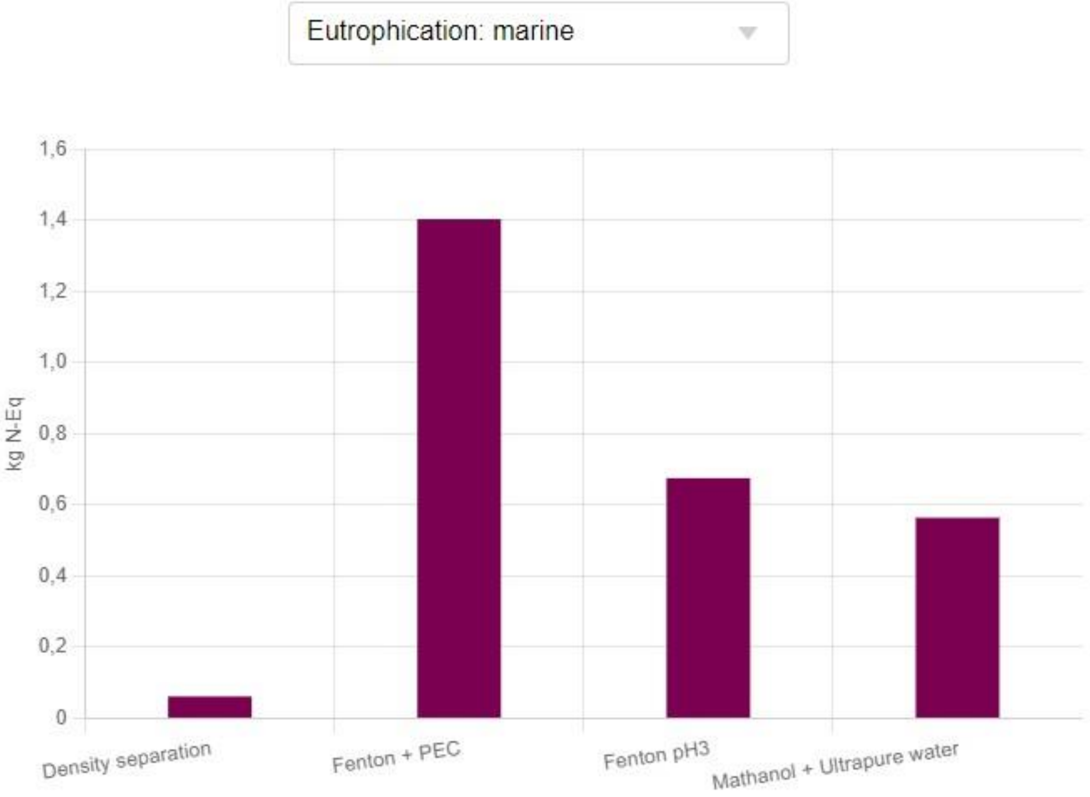
Appendix A. Result for the LCA, Definitive numbers, not adjusted

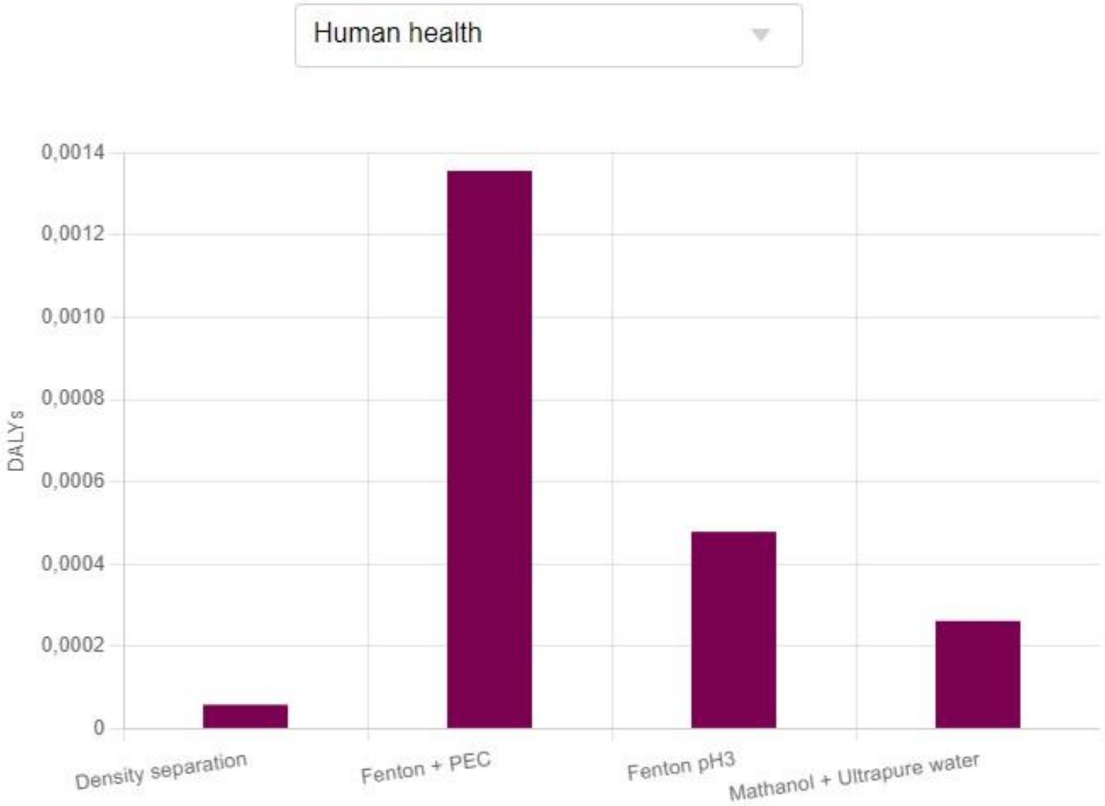
Note that the label “Mathanol + Ultrapure water” refers to “Methanol + Ultrapure Water + PEC” and “Density Separation” refers to “Density Separation + PEC” but the authors lost the access to the original work and could not re-label the graphs.





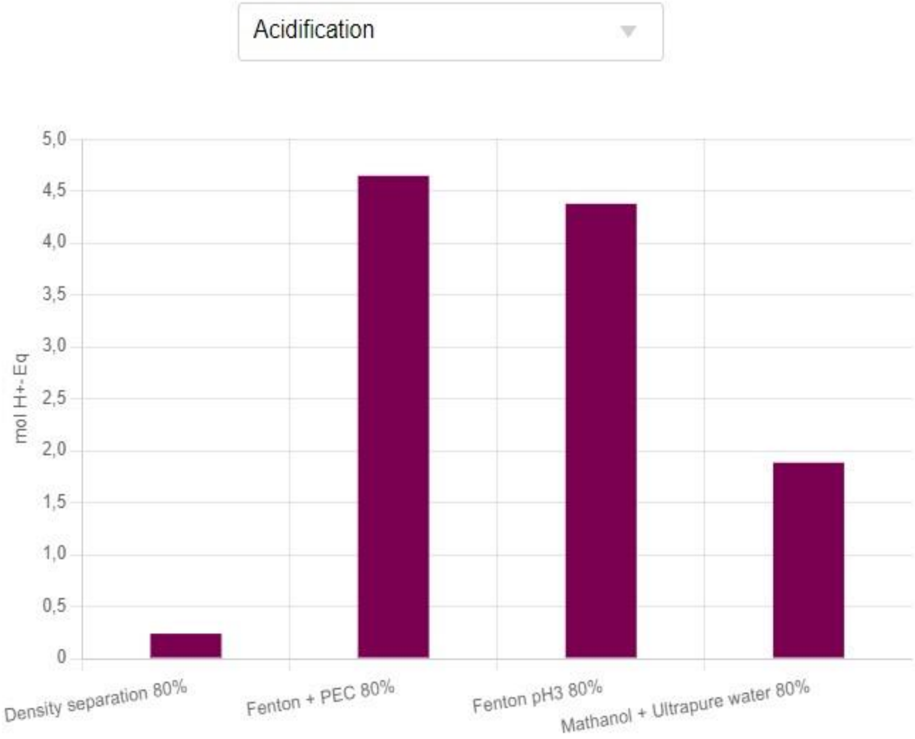

Ecotoxicity: freshwater
CTUe
7 000
6 000
5 000
4 000
3 000
2 000
1 000
0
Density separation
Fenton + PEC
Fenton pH3
Mathanol + Ultrapure water

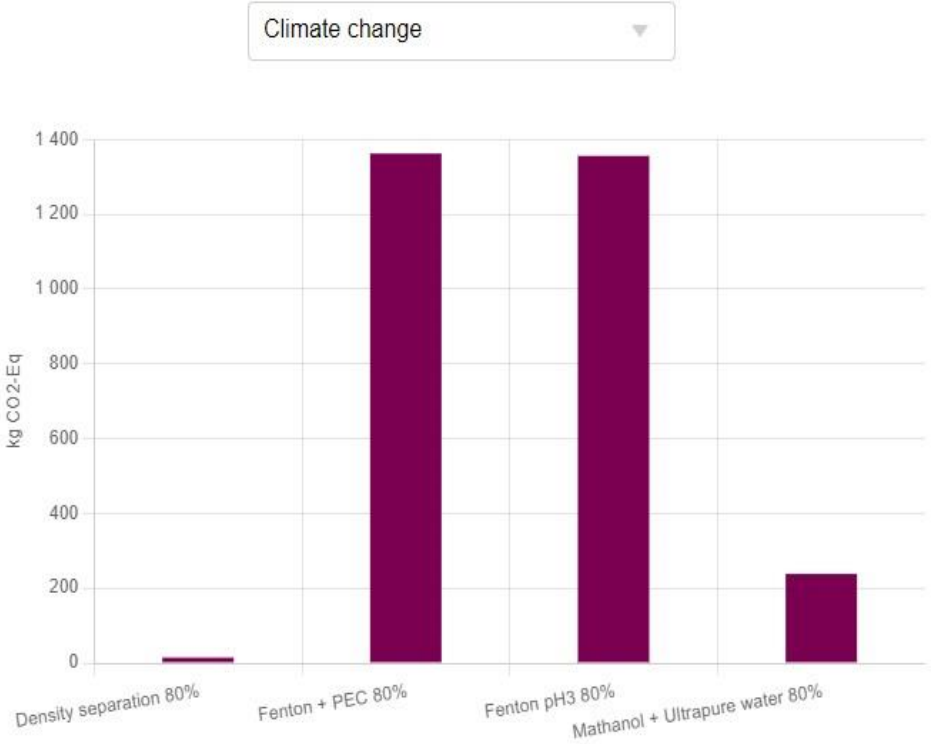

Eutrophication: marine
kg N-Eq
1,6
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0
Density separation
Fenton + PEC
Fenton pH3
Mathanol + Ultrapure water

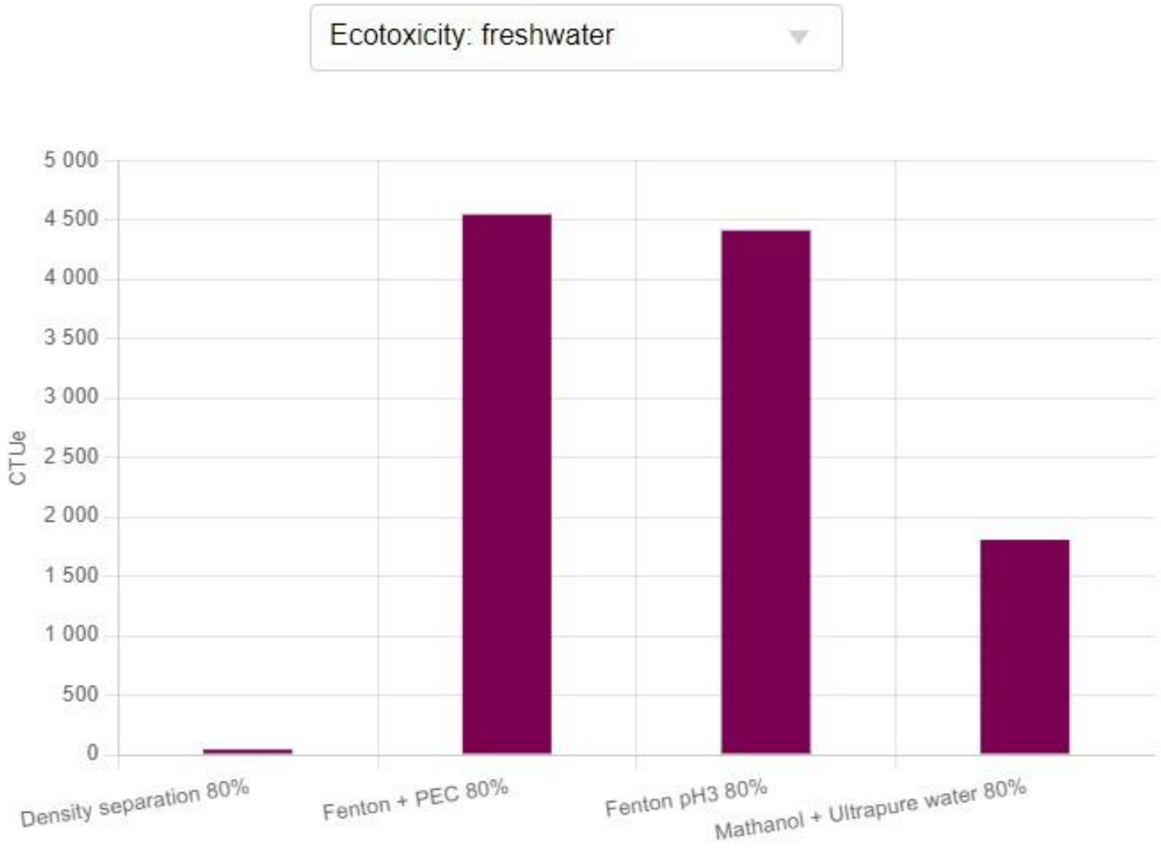

Human health
DALYs
0,0014
0,0012
0,0010
0,0008
0,0006
0,0004
0,0002
0
Density separation
Fenton + PEC
Fenton pH3
Mathanol + Ultrapure water

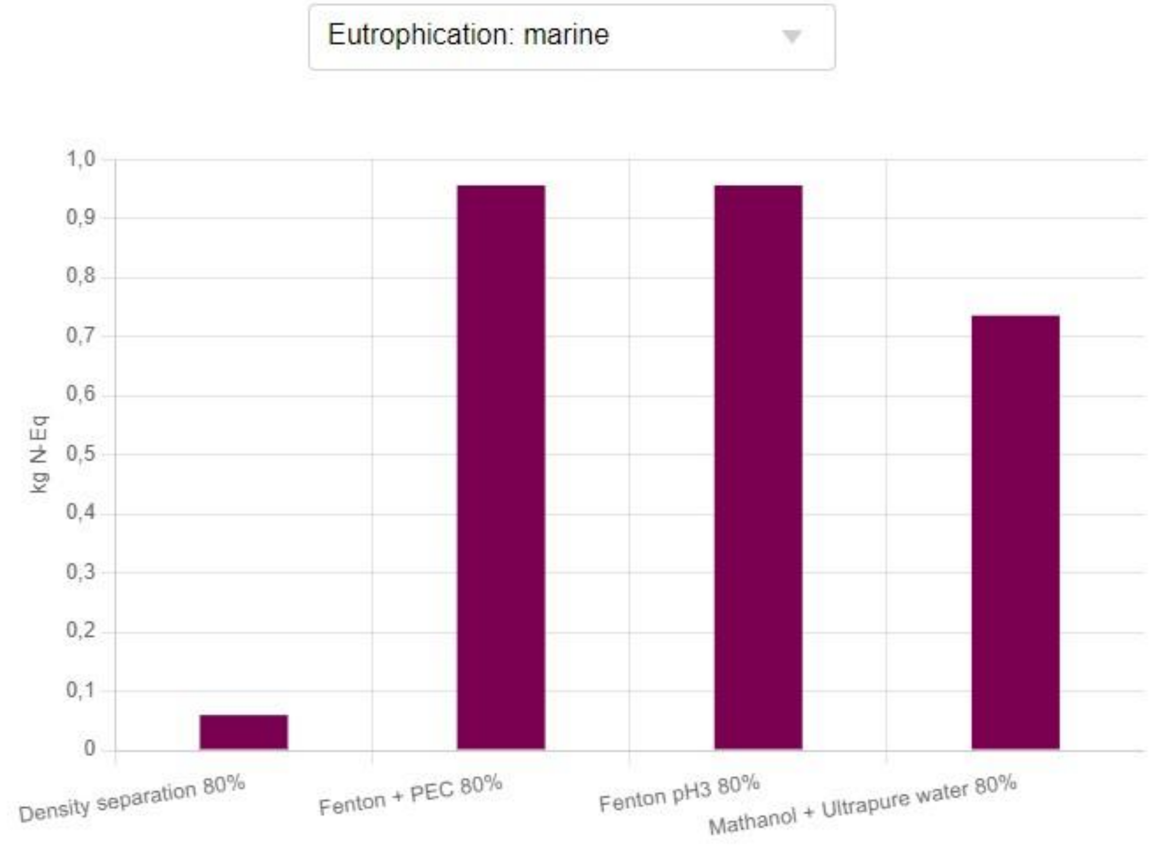
Appendix B. Result for LCA, Definitive numbers, 80% adjusted

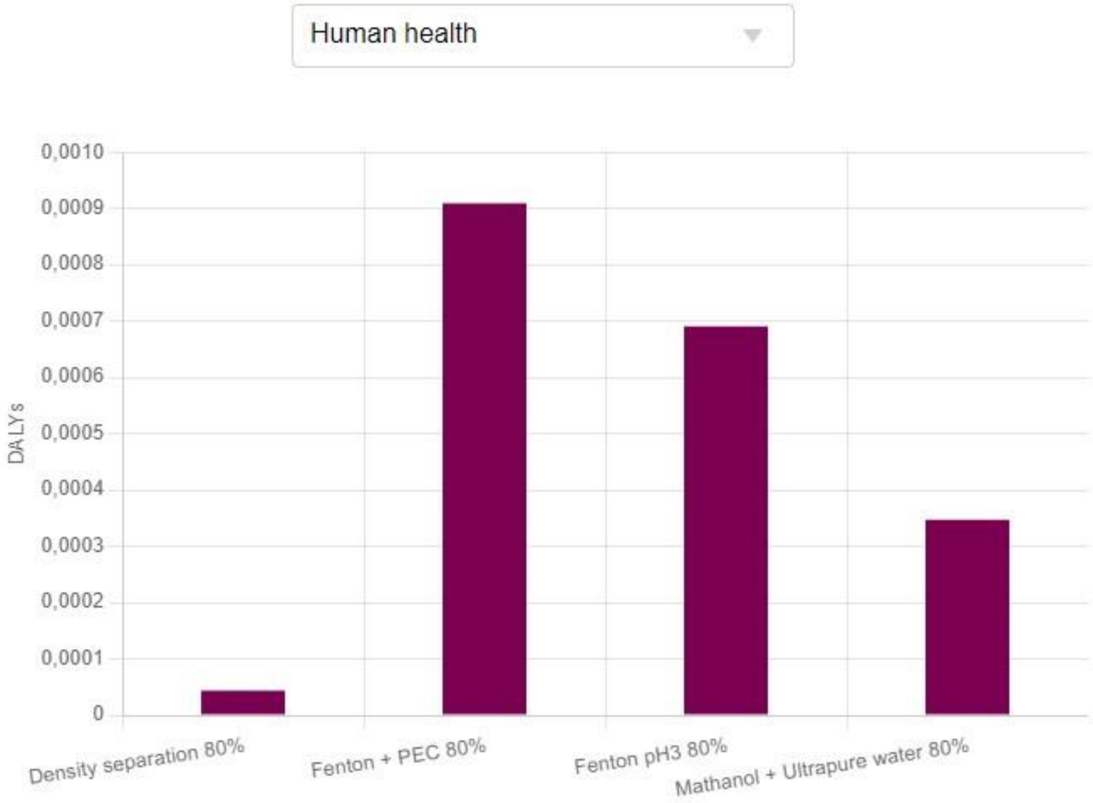
Note that the label “Mathanol + Ultrapure water” refers to “Methanol + Ultrapure Water + PEC” and “Density Separation” refers to “Density Separation + PEC” but the authors lost the access to the original work and could not re-label the graphs.






Ecotoxicity: freshwater
CTUe
5 000
4 500
4 000
3 500
3 000
2 500
2 000
1 500
1 000
500
0
Density separation 80%
Fenton + PEC 80%
Fenton pH3 80%
Mathanol + Ultrapure water 80%

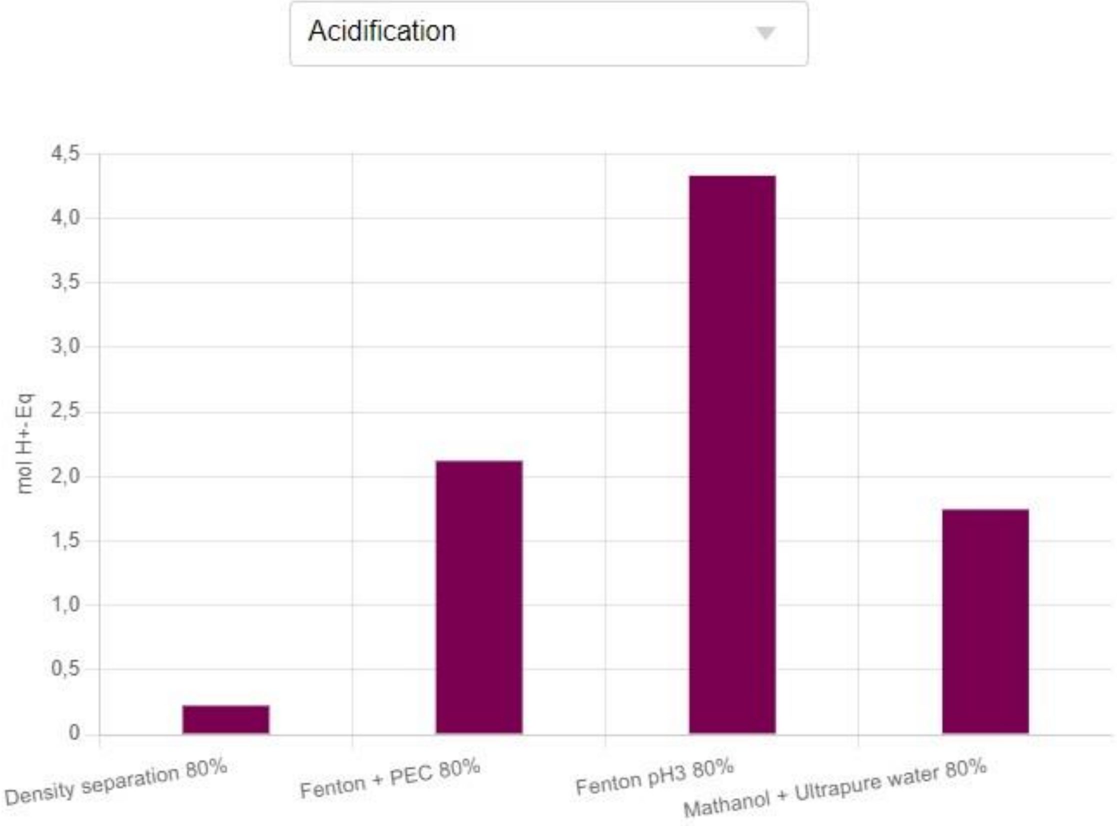

Eutrophication: marine
kg N-Eq
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
Density separation 80%
Fenton + PEC 80%
Fenton pH3 80%
Mathanol + Ultrapure water 80%

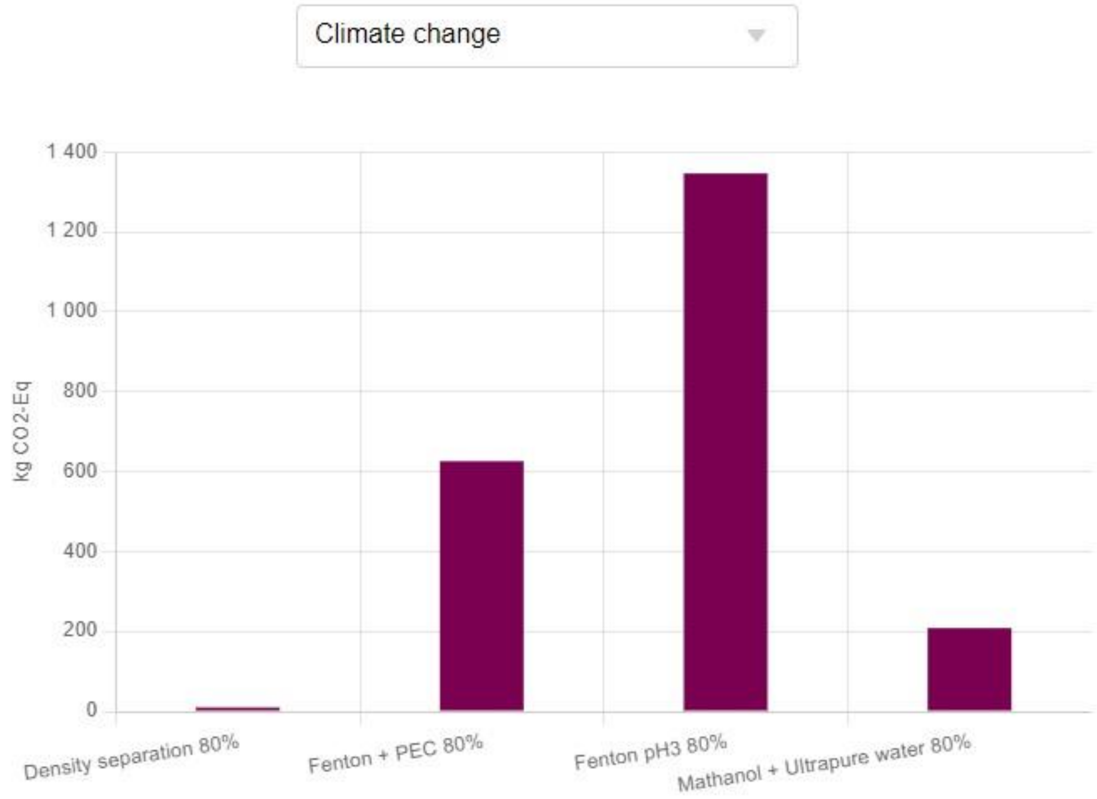


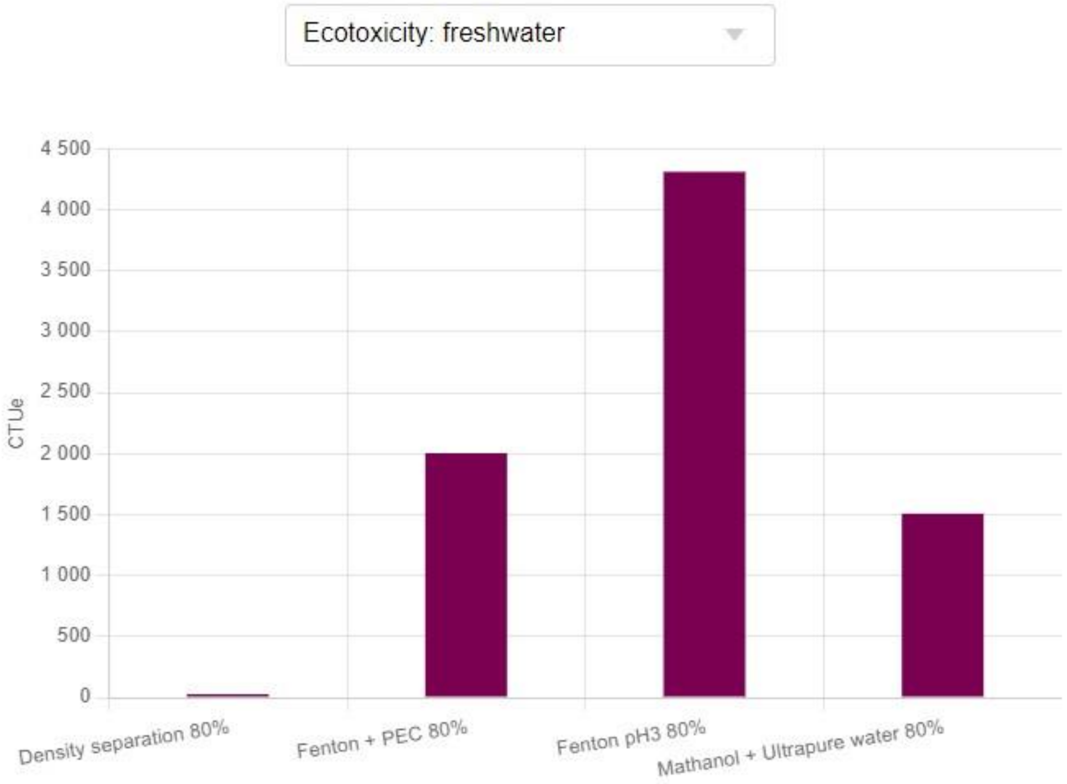
Human health

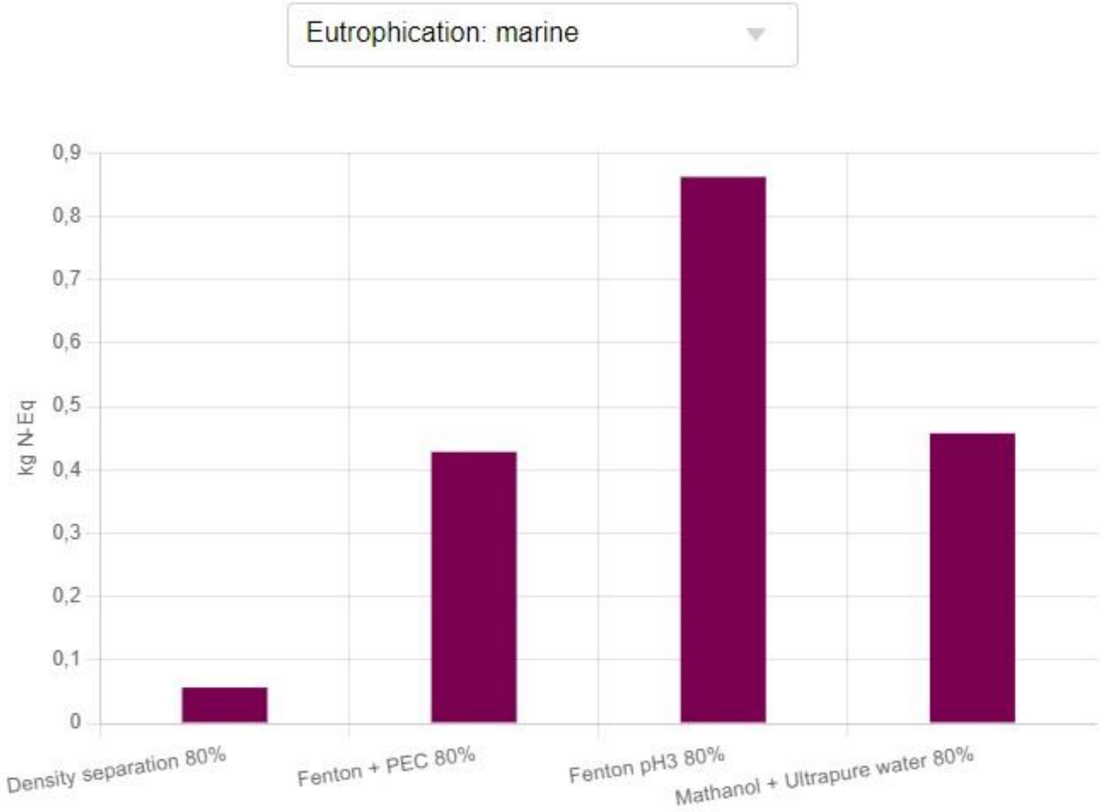
Appendix C. Result for LCA, Definitive numbers, 80% adjusted, sensitivity analysis adjusted

Note that the label “Mathanol + Ultrapure water” refers to “Methanol + Ultrapure Water + PEC” and “Density Separation” refers to “Density Separation + PEC” but the authors lost the access to the original work and could not re-label the graphs.

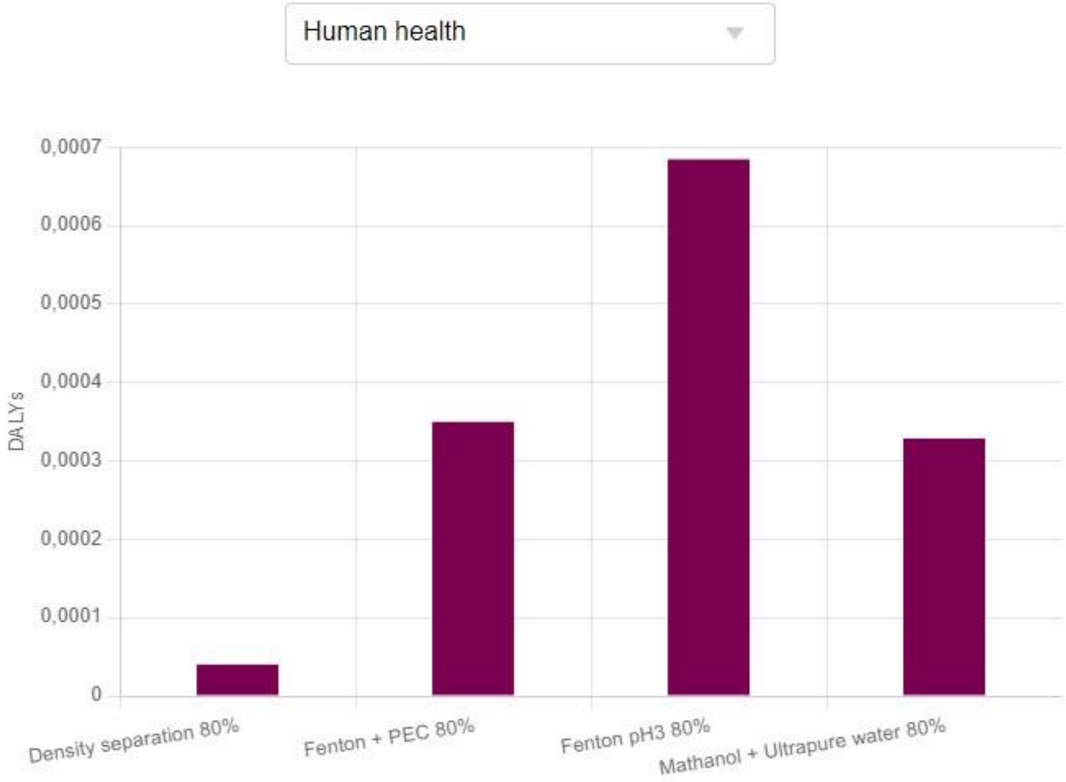



Climate change
kg CO2-Eq
1 400
1 200
1 000
800
600
400
200
0
Density separation 80%
Fenton + PEC 80%
Fenton pH3 80%
Mathanol + Ultrapure water 80%


Ecotoxicity: freshwater
CTUe
4 500
4 000
3 500
3 000
2 500
2 000
1 500
1 000
500
0
Density separation 80%
Fenton + PEC 80%
Fenton pH3 80%
Mathanol + Ultrapure water 80%



Eutrophication: marine



Human health

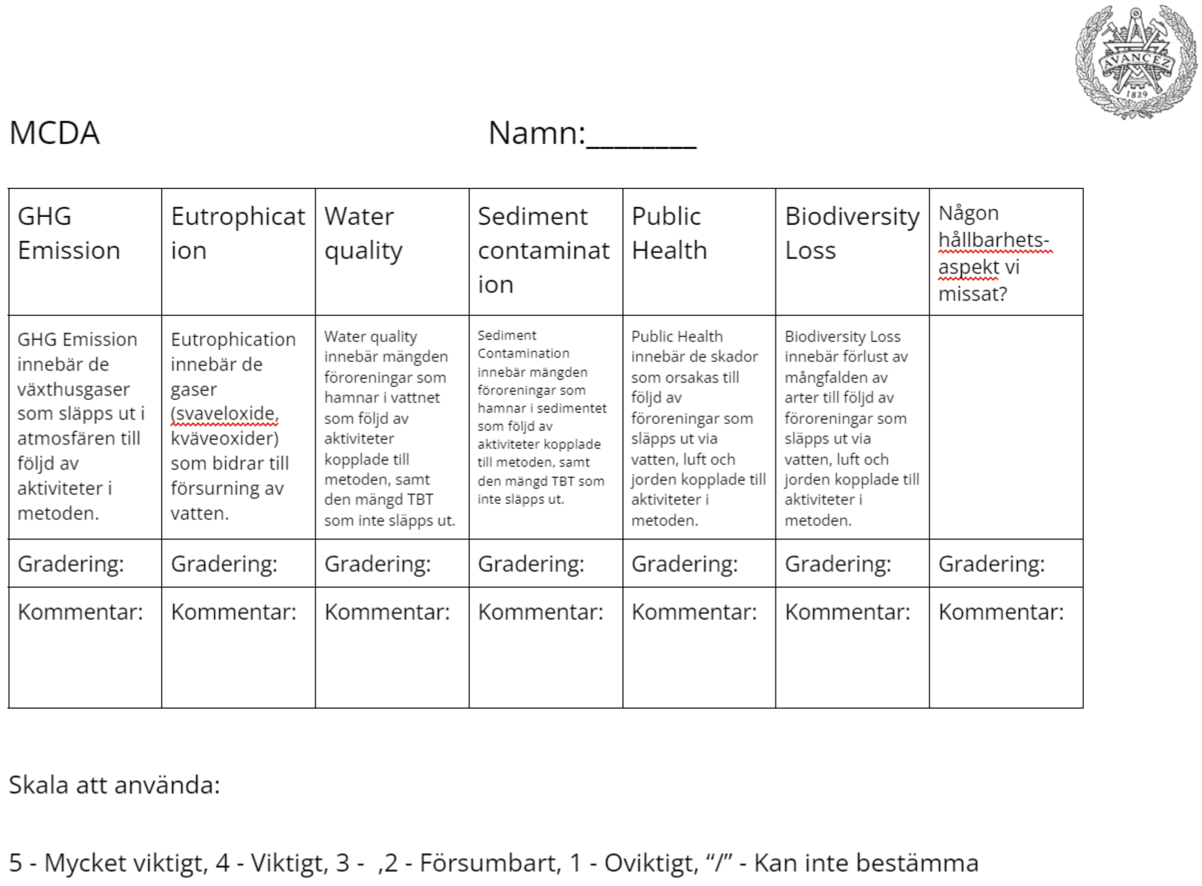
Appendix D. Question sent for the initial survey in the MCDA

We will conduct an LCA/MCDA. What sustainabillity aspect are relevant to the project?

(If you do not know what to answer, just answer on your gut feeling)

	1. Most important.	2. Important.	3. Indifferent (can be checked, but not that important)	4. Unimportant	5. Completely unrelevant
Displacement of Communities	○	○	○	○	○
Access to Waterways	○	○	○	○	○
Job Creation	○	○	○	○	○
Research and development of technology	○	○	○	○	○
Public Health	○	○	○	○	○
Recreational Opportunities	○	○	○	○	○
Disruption of Daily Activities	○	○	○	○	○
Public acceptance to dumping to sea	○	○	○	○	○
Cost of Dredging	○	○	○	○	○
Variable Costs	○	○	○	○	○
Fixed Costs	○	○	○	○	○
Soil Quality	○	○	○	○	○
Energy Consumption	○	○	○	○	○
Water Quality	○	○	○	○	○
Sediment Contamination	○	○	○	○	○
Biodiversity Loss	○	○	○	○	○
Eutrophication	○	○	○	○	○
Marine Debris	○	○	○	○	○
Emissions	○	○	○	○	○
Effect on shipping industry	○	○	○	○	○

Appendix E. Material used for the workshop



MCDA Namn:_______

GHG Emission	Eutrophication	Water quality	Sediment contamination	Public Health	Biodiversity Loss	Någon hållbarhets-aspekt vi missat?
GHG Emission innebär de växthusgaser som släpps ut i atmosfären till följd av aktiviteter i metoden.	Eutrophication innebär de gaser (svaveloxide, kväveoxider) som bidrar till försurning av vatten.	Water quality innebär mängden föroreningar som hamnar i vattnet som följd av aktiviteter kopplade till metoden, samt den mängd TBT som inte släpps ut.	Sediment Contamination innebär mängden föroreningar som hamnar i sedimentet som följd av aktiviteter kopplade till metoden, samt den mängd TBT som inte släpps ut.	Public Health innebär de skador som orsakas till följd av föroreningar som släpps ut via vatten, luft och jorden kopplade till aktiviteter i metoden.	Biodiversity Loss innebär förlust av mångfalden av arter till följd av föroreningar som släpps ut via vatten, luft och jorden kopplade till aktiviteter i metoden.	
Gradering:	Gradering:	Gradering:	Gradering:	Gradering:	Gradering:	Gradering:
Kommentar:	Kommentar:	Kommentar:	Kommentar:	Kommentar:	Kommentar:	Kommentar:

Skala att använda:

5 - Mycket viktigt, 4 - Viktigt, 3 - ,2 - Försumbart, 1 - Oviktigt, “/” - Kan inte bestämma

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY