MASTER'S THESIS ACEX30

Treatment of polluted sediment through sediment washing and photoelectrocatalysis.

Master's Thesis in Infrastructure and Environmental Engineering

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Water Environmental Technology
Urban Water and Contaminated Materials
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2023

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ABSTRACT

There are significant amounts of metals and organic pollutants found in aquatic environments due to an increase in urbanization and industrialization. These contaminated sediments are usually dredged out from the depth of the water in waterways for the safety of water transport and also from stormwater sediment ponds to reinstate their original capacity for settling of suspended solids. While it used to be common practice to dispose of contaminated sediments at sea, this is now often prohibited. Landfilling serves as an alternative, yet the challenge of mass management of contaminated sediments is a rising problem due to its high cost for remediation and limited available space for dumping. This thesis aims to investigate innovative sediment remediation techniques, through sediment washing by using eco-friendly leaching agents followed by photoelectrocatalysis (PEC), to address contamination challenges in sediment from both a marina and traffic runoff. PEC combines photocatalysis and electrocatalysis to effectively degrade organic pollutants and recover metals from polluted water. The study reveals promising results, with leaching methods showing potential in reducing copper (Cu) and zinc (Zn) concentration in traffic runoff sediment, although the marina sediment presented challenges. While reductions in organotin compounds, specifically tributyltin (TBT) and polycyclic aromatic hydrocarbons (PAH), were observed in the sediments, achieving significant risk class level reductions remained elusive. Optimal leaching agent selection for metal extraction proved to be difficult, yet the potential for metal extraction from sediment was evident. PEC treatment demonstrated potential in reducing Cu and Zn concentration from the leachates, requiring further study on metal recovery and environmental risk mitigation. For organic pollutants, a combination of soap and methanol with a reduction of up to 70% of TBT emerged as an effective leaching agent, with challenges when addressing both metals and organic pollutants. PEC showed potential in organic pollutant degradation (up to 99%) in the leachates. In conclusion, this research contributes valuable insights into the complexity of sediment washing, metal extraction, and organic pollutant degradation using PEC. It emphasizes the need for further investigations and highlights the importance of considering site-specific attributes when implementing remediation approaches.

Keywords: Contaminated sediment, organic pollutants, toxic metals, leaching, photoelectrocatalysis, sediment washing, traffic runoff.

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Masegongliu Kamei

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List of Acronyms

DBT	Dibutyltin
ISQG/TEL	Interim marine sediment quality guidelines/threshold effect levels
LCA	Life cycle analysis
LSLU	Less sensitive land use
MBT	Monobutyltin
OTCs	Organotin compounds
PAH	Polycyclic aromatic hydrocarbon
PAH- L	Low molecular weight Polycyclic aromatic hydrocarbon
PAH- M	Moderate molecular weight Polycyclic aromatic hydrocarbon
PAH- H	High molecular weight Polycyclic aromatic hydrocarbon
PEC	Photoelectrocatalysis
PEL	Probable effect level
SLU	Sensitive land use
Swedish EPA	Swedish Environmental Protection Agency
TBT	Tributyltin

1 Introduction

Sea transport accounts for 80% of global transport today (United Nations, 2018). For this purpose, sediments must be continuously dredged out from the depth of the water in waterways, estuaries, and ports to assure safety in sea transport(Wang et al., 2022). A significant amount of metals and organic pollutants can be found in sediments from ports, marinas, and waterways (Das et al., 2014; Norén, 2021). Organic pollutants such as organotin compounds (OTCs) have been used for many years as an antifouling agent in paints applied to boats and fishnets(Filipkowska et al., 2014). Consequently, worn paint flakes containing OTCs get settled and are now commonly found in marine sediments in concentrations hazardous to aquatic life (Antizar-Ladislao, 2008; Filipkowska et al., 2014). Furthermore, OTCs are proven to be environmentally persistent and have a high ability to transfer into the ecosystem which may cause destruction to the immune and reproductive systems in both humans and the aquatic environment (National Center for Biotechnology Information, 2023; Veltman et al., 2006).

For centuries, metals have been an essential part of our daily life. For instance, metals are used in jewellery, cars, electronics, construction materials, and machinery. Metals are naturally occurring minerals and are often found in sediment. However, its excessive quantity in sediment is due to anthropogenic activities but also due to its usage as an antifouling agent in boats that ultimately gets accumulated in sediment. (Astatkie et al., 2021). Toxic metals in sediments get transferred indirectly to humans through the food chain. It is therefore of high importance to investigate the concentration of toxic metals in the aquatic environment by measuring their concentration in sediments.

Due to their high pollutant content of toxic metals and organic pollutants, dredged sediments cannot be used for many purposes, such as construction. As of 2018, 86% of dredged sediments are either disposed of at sea or in landfills (Naturvårdsverket, 2018). Therefore, to promote sustainability and a clean environment, it is vital to treat contaminated dredged sediments that could increase the use of repurposing and reduce mass management problems.

In addition to marine sediment, traffic runoff sediment is also an interest of concern. Pollutants from traffic are washed off by stormwater into sewer drainage that ultimately ends up in receiving water. This contributes to the contamination of catchment area sediments such as rivers and lakes that may be used as drinking water sources or end up in the sea, and thus, poses ecological risks and human risks (Krein & Schorer, 2000). A common practice for treating urban runoff is by using wet retention ponds. It is a practice in which stormwater is treated through sedimentation. Maintenance of the sediment pond is done by removing sediment that is usually contaminated from the bottom of the pond and disposing it into landfills. Traffic runoff sediments are highly polluted with a cocktail of both particles and pollutants such as for example metals and polycyclic aromatic hydrocarbons (PAH). The main sources of PAH are mostly vehicle tires and road wear from asphalt pavements, combustion, and oils (S. Gao et al., 2022; Markiewicz et al., 2017; Trafikverket, 2018) As for metals, the sources of pollution are traffic emission and abrasion, atmospheric deposition, brake pads, corrosion, fuel, paint, and road equipment (Müller et al., 2020). The level of this pollution is influenced by different factors such as precipitation, maintenance of roads, traffic density, etc.

Sediment treatment is a challenge because most methods of treatment can only effectively treat a specific type of pollutant. This stimulates the need to investigate possible combinations of treatment methods to remove different types of pollutants in dredged sediment. Besides removing pollutants, recovering metals, and reusing in society are prominent (Fathollahzadeh et al., 2012). This is because the demand and cost for metals are increasing and are expected to increase in the future.

Soil washing is a common practice for contaminated soil. However, studies on sediment washing are limited especially concerning eco-friendly leaching agents' remediation methods. (Norén et al.2021) conducted a study on polluted sediment using different environmentally friendly leaching agents and determined that it is possible to wash out tributyltin (TBT) and metals using Milli-Q water, and soap (saponified tall oil). However, the contaminants are found in the leachate, necessitating the treatment of these leachates.

Photoelectrocatalysis PEC is an emerging and widely studied treatment method in wastewater technology (Alulema-Pullupaxi et al., 2021; Bessegato et al., 2018; Kusmierek, 2020; Peleyeju & Viljoen, 2021; Ye et al., 2021). It is a method that combines photocatalysis and electrocatalysis to effectively degrade organic pollutants and recover metals from polluted water. While the application of this treatment method in sediment treatment is relatively less known, this study intends to develop sediment treatments for organic pollutants and metals by leaching pollutants from sediment through sediment washing into a water phase and treating the water using photoelectrocatalysis (PEC).

1.1 Aim

The aim of this project was to combine two different treatment methods to investigate if a stepwise treatment scheme could remove both organic and inorganic pollutants from sediment. Detergents were used to dissolve inorganic and organic pollutants into the water phase and subsequently, PEC treatments were used to degrade organic compounds and recover metal from the leachate.

To fulfill the aim the following research questions were proposed:

- How much TBT, PAH, and metals could be washed out from the sediment with a detergent such as soap as a leaching agent?
- How much of the TBT and PAH could be degraded in the washing liquid with the use of PEC? And how much of the Cu and Zn could be recovered with this method?

1.2 Limitations

This study had some limitations to consider. Firstly, the study primarily focuses on the effectiveness of the treatment method and did not include tests to check for toxicity or the mobility of contaminants. Additionally, the complexity of different metal ions and the potential effects of their corrosion by-products were not explored. Keep in mind that the sediment samples used in the study were not entirely homogeneous, potentially causing some variability in the findings. Lastly, due to budget constraints, duplicate samples were not feasible, which could have enhanced result reliability. Hence, the results should be seen as indicative rather than absolute.

2 Theoretical background

This thesis is divided into three parts. The first part comprises a literature study to give an understanding of the theoretical background to this thesis conerning pollutants in sediment, their sources, their classification criteria, and sediment treatment. The second part which will be discussed in Chapter 3, comprises the collection, setup, and classification of the samples and the laboratory experiments with the intention of investigating efficient and environmentally friendly methods to remove pollutants from polluted sediment. The last part, which will be discussed in Chapter 4, contains a chemical analysis of samples that were sent to a commercial laboratory.

This chapter contains the first part, the literature study of the thesis describing sediments, metals, TBT, and PAH together with their classification criteria in the context of sediments and water. It also provides a basic description of pollutants leaching and photoelectrocatalysis (PCE).

2.1 Sediments

Sediments are soil particles that are deposited through erosion by factors such as wind, water, glaciers, and gravity (Department of the Navy, 2017). It could include rocks, minerals or vegetation and animal remains. Sediment particles vary in size and is often categorized in terms of particle size, it could be gravel, sand, silt, or sand (Wetzel et al., 2001). Sediments are an essential part of the growth of the aquatic system, however, excessive and lack of sediment, or the level of contamination could influence the aquatic ecosystem negatively (DFO Pacific Region, 2000). Sediments in water bodies are often small particles and mineral based. These are often dependent on the geology of the location (Haughton et al., 1991).

Minerals and organic materials are usually present in sediments, which originate both from aquatic and terrestrial organisms (Norén, 2021). Sediments act as a bank for the accumulation of pollutants that originate from anthropogenic activities such as urbanization, agriculture, maritime transport, and industrialization (Apitz et al., 2005). Due to this accumulation of pollutants, contaminated sediment can pose adverse effects on aquatic ecosystems. Pollutants such as toxic metals, persistent organic pollutants for example PAH, organotin compounds such as tributyltin (TBT), dibutyltin (DBT) and monobutyltin (MBT), pharmaceuticals, and nutrients are commonly found in contaminated sediments (Norén, 2021). Due to the variation of pollutant types in sediment, decision-making and management are often difficult and complex (Apitz et al., 2005). However, ecological assessment and management options could be conducted, provided the content of pollutants in the sediment is investigated. (Norén, 2021)

2.2 Metals

Metals in aquatic environments have been a concern for many years. It occurs naturally due to erosion, weathering, or volcanism and from anthropogenic activities such as urbanization and industrialization (Liang et al., 2018; Pan et al., 2020; Perumal et al., 2021; Sadak, 2023). Metals accumulate in sediments once they enter the marine environment (Perumal et al., 2021; H. Wang et al., 2021) and are considered to have a higher concentration in sediments as compared to surface water (Scheibye et al., 2014). Metals are hazardous and pose a threat to public health. The toxicity level of metals depends on the dosage of exposure, concentration, and types of metals (Sadak, 2023; Wang et al., 2021). For example, Cu, Ni, and Zn act as nutrients for plants and animals, however, an excessive amount of concentration could be toxic. On the other hand, metals such as As, Cd, Cr, Hg, and Pb cause serious health problems upon exposure even at low concentrations (Sadak, 2023). Metals such as Cu and Zn were commonly used as antifouling agents in the painting industry and therefore typically accumulated in sediment along with tributyltin (TBT) (Singh & Turner, 2009). Furthermore, in traffic runoff pollution, traces of metals such as Cd, Cr, Pb, Ni, Cu, and Zn can be found (Opher & Friedler, 2010). The most common are Cu, Zn and Pb which originate from vehicle break emissions (Cu) and tire wear (Zn), lubricating oil/grease (Pb) and corrosion of galvanized parts (Cu and Zn) (Legret & Pagotto, 1999; Mangani et al., 2004)

The presence of toxic metals in sediment requires urgent attention both for the aquatic environment and humans (Astatkie et al., 2021). Additionally, the demand for metals is increasing and is expected to continuously increase. However, metal production has a high impact on the environment. Therefore, to reduce the negative environmental footprint, metal recovery creates an opportunity to meet metal supply demand to a certain extent. Recovery of metal from sediment could be possible, however, metal content in sediment is significantly low to meet the demand (Norén, 2021). Nonetheless, if the management and treatment of sediments can be improved, a higher amount of metals can be recovered which will also eventually simplify mass management challenges.

The most toxic metals are As, Pb, Cd, Cr, Cu, Hg, Ni, Zn that are often listed in sediment and water quality standards. Table 1 presents the guideline values of metals from the City of Gothenburg for release of polluted water into watercourses, and classification according to the Swedish EPA for lakes and watercourses. Table 2 presents the guideline values of metals from the Swedish guideline values for contaminated soil together with the Canadian Council of Ministers of the Environment (CCME) and Norwegian guideline values of metals for sediments respectively. It is to be noted that the Swedish classification for sediment does not indicate the toxicity level. To supplement the Swedish guideline values, Norwegian and Canadian guideline values were used as these countries share comparable geology and climate (INSURE, 2017). There are no guidelines available for the disposal of sediment in Sweden and therefore soil contamination guidelines are used since they are generally relevant to specify sediment disposal alternatives with the aid of leaching tests before disposal (Norén et al., 2021).

Table 1: Guideline values of metals for release of polluted water into watercourses from the City of Gothenburg, and classification according to the Swedish EPA for lakes and watercourses (Göteborgs Stad, 2020; Lindberg, 2001)

Metals	**Gothenburg guidelines effluent value [µg/L]**	**Swedish EPA guideline value for lakes and watercourses [µg/L]***				
		Class 1	Class 2	Class 3	Class 4	Class 5
		(Very Low)	(Low)	(Moderately low)	(High)	(Very high)
As	16	<0.4	0.4-5	5-15	15-75	75

Pb	28	<0.2	0.2-1	1-3	3-15	>15
Cd	0.9	<0.01	0.01-0.1	0.1-0.3	0.3-1.5	>1.5
Cu	10	<0.5	0.5-3	3-9	9-45	>45
Cr	7	<0.3	0.3-5	5-15	15-75	>75
Hg	0.07	-	-	-	-	-
Ni	68	<0.7	0.7-15	15-45	45-225	>225
Zn	30	<5	5-20	20-60	60-300	>300

*Risk of biological effects: Class 1=none or very little; Class 2=little; Class 3=primarily in acidic water and in soft water with low concentration of humus and nutrients; Class 4= increased risk; Class5= high risk even with brief exposure

Table 2: Swedish EPA guidelines for contaminated soil, together with Canadian, and Norwegian sediment guidelines for metals (Naturvårdsverket, 2022; CCME, 1999; Miljødirektoratet, 2020).

Metals	Swedish EPA for soil* [mg/kg]		CCME** [mg/kg]		Norwegian guideline value *** [mg/kg]				
	SLU	LSLU	ISQG/ TEL	PEL	Class 1	Class 2	Class 3	Class 4	Class 5
As	10	25	7.24	41.6	15	18	71	580	>580
Pb	50	180	30.2	112	25	150	1 480	2 000	2 500
Cd	0.8	12	0.7	4.2	0.2	2.5	16	157	>157
Cu	80	200	18.7	198	20	84	84	147	>147
Cr	80	150	52.3	160	60	620	6 000	15 500	25 000
Hg	0.25	25	0.13	0.7	0.05	0.52	0.75	1.45	>1.45
Ni	40	120	-	-	30	42	271	533	>533
Zn	250	500	124	271	90	139	750	6 690	>6 690

*SLU=sensitive land use; LSLU=less sensitive land use

**ISQG/TEL=interim marine sediment quality guidelines/threshold effect levels, < TEL= adverse effects rarely occur; PEL=probable effect level, < PEL = adverse effects occasionally occur; > PEL= adverse effects frequently occur.

***Class 1=background levels; Class 2=no toxic effects; Class 3=toxic effects following chronic exposure; Class 4=toxic effects following short term exposure; Class 5 = severe acute toxic effects.

2.3 Tributyltin

Tributyltin (TBT) belongs to the group of organotin compounds (OTCs) and has hydrophobic properties. It is a toxic chemical that has been used for different industrial applications, for example, antifouling agents, disinfection in industrial cooling water systems, antifungals in the textile industry, and slime control in paper mills (Antizar-Ladislao, 2008). TBT was popularly used as an antifouling agent in boat paint and hence, this contributes as one of the main pollutant sources to the marine ecosystem. In the early 1970s, studies on TBT became of interest when its connection to imposex phenomena of normal female gastropods commonly known as snails or slugs was reported in the UK (Blaber, 1970).TBT has the ability to disrupt hormones, hence this imposex occurs due to bioaccumulation of TBT that disrupts the endocrine system of gastropods. This results in the growth of testosterone levels and therefore causes imposex (Bryan et al., 1989; Horiguchi et al., 1998). Additionally, studies have shown how TBT has spread in the food chain through bioaccumulation and biomagnification (Veltman et al., 2006).This means that the concern about TBT is extended profoundly not just in the aquatic ecosystem and marine environment but also in the terrestrial environment and ultimately to humans as well. Various efforts have been taken globally and restriction on the use of TBT as an antifouling was imposed to protect the aquatic environment. The use of TBT was banned in Sweden since the 1989 (Sternbeck et al., 2006).

TBT can be degraded through the debutylation process. It is a process in which TBT is degraded progressively into less toxic compounds by dealkylation meaning degradation of TBT to dibutyltin (DBT), monobutyltin (MBT), and finally to inorganic tin(Dowson et al., 1996; Dubey & Roy, 2003), see Figure 1. The degradation process can be accelerated with exposure to UV radiation, high temperature, and other biological activity (Barug, 1981; Dowson et al., 1996). Studies have shown that TBT degrades faster in water than in sediment with a range of 6 weeks to 5 months of half-life degradation. Whereas it takes tens of decades to degrade in sediment possibly due to less exposure to sunlight and anaerobic condition (Antizar-Ladislao, 2008; Dowson et al., 1996). This indicates the conservative characteristic of sediment. Furthermore, this implies that the current and future restrictions on TBT will not promptly eliminate the TBT pollutants from the marine environment and aquatic ecosystem. Therefore, it is vital to develop innovative and sustainable ways to treat TBT from sediments.

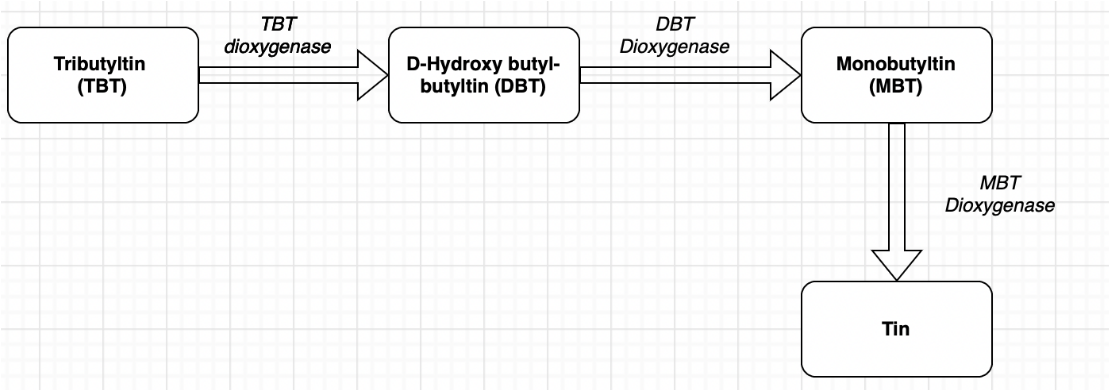

Figure 1: Schematic diagram of the TBT degradation process

Table 3 presents the list of OTCs along with Swedish guideline values for sediment and soil together with the guideline values from the Canadian Council of Ministers of the Environment (CCME) and Norwegian guideline values for sediments. Table 4 presents the guideline values for OTCs from the City of Gothenburg for release of polluted water into water courses together with guidelines from CCME for freshwater and marine water, and from the European Union for surface water/freshwater.

Table 3: Swedish guideline values of organotin for sediment and soil together with Canadian and Norwegian guidelines for sediment. (Naturvårdsverket, 2022; Josefsson, 2017; CCME, 1999; Miljødirektoratet, 2020).

Organotin	Swedish EPA for soil * [µg /kg]		Swedish guideline value for sediment** [µg /kg TS]					Norwegian guideline value *** [µg /kg TS]				
	SLU	LSLU	Class 1	Class 2	Class 3	Class 4	Class 5	Class 1	Class 2	Class 3	Class 4	Class 5
TBT	150	300	<1		10	20	≥20	0	0.002	0.016	0.032	>0.032
DBT	1500	5 000	<1		10	26	≥26	-	-	-	-	-
MBT	250	800	<1		19	55	≥55	-	-	-	-	-

*SLU=sensitive land use; LSLU=less sensitive land use; Swedish guideline: Class1=very low content; Class 2= low content; Class 3=medium content; Class 4=high content; Class 5=very high content.
**ISQG/TEL=interim marine sediment quality guidelines/threshold effect levels, < TEL= adverse effects rarely occur; PEL=probable effect level, < PEL = adverse effects occasionally occur; > PEL= adverse effects frequently occur.
***Norwegian guideline: Class 1=background levels; Class 2=no toxic effects; Class 3=toxic effects following chronic exposure; Class 4=toxic effects following short term exposure; Class 5 = severe acute toxic effects

Table 4: Guideline values of OTCs from the City of Gothenburg for release of polluted water into water courses, together with Canadian guidelines for freshwater/marine and European Union guidelines for surface water/freshwater (Göteborgs Stad, 2020; CCME, 2010; European Communities, 2008).

Organotin	**Gothenburg guidelines effluent value [µg/L]**	**CCME [µg/L]**		**EU [µg/L]**		
		Freshwater	Marine	AA inland surface water	AA other surface water	MAC surface water
TBT	0.0015	0.008	0.001	0.0002	0.0002	0.0015
DBT	-	-	-	-	-	-
MBT	-	-	-	-	-	-

AA=annual average; MAC=maximum allowable concentration

2.4 Polycyclic Aromatic Hydrocarbon (PAH)

Polycyclic Aromatic Hydrocarbons (PAH) is a group of chemical compounds that occurs naturally in coal, oil, and gasoline (Phillips, 1999). PAH is a type of aromatic hydrocarbon of two or more benzene rings fused together with multiple ring structures. The molecules do not carry heteroatoms or other substituents meaning PAH rings are only bounded by carbon and hydrogen in their system (Lawal, 2017). PAH is persistent and can be found everywhere in the environment. PAH occurs with different structural components and is categorized based on the number of rings. In Sweden, among the hundred types of PAH, sixteen are classified based on their physical-chemical properties and toxicity levels. These PAH-16 are categorized into three groups namely, PAH-L, PAH-M, and PAH-H which stand for low, medium, and high molecular weight respectively(Naturvårdsverket, 2017).

Exposure to PAH in humans is inevitable. The prime exposure route to humans is through the consumption of contamination from environmental sources, food processing in industry, smoking, and other domestic cooking practices such as the type of fossil fuels used for cooking or heat for the house (Fabian et al., 1997). Furthermore, PAH can enter the food web through soil and water. One of the main sources of PAH contamination in surface water is urban runoff (Agarwal, 2009; Z. Gao et al., 2023). This is because motor vehicle tires contain PAH and due to abrasion, PAH is washed down into the road drainage system by stormwater that gets accumulated in traffic runoff sediment. This is further corroborated by a study, particularly in Gothenburg that shows the main sources of PAH from a highway traffic runoff are tire and road surface wear, break lining, vehicle exhaust gases and lubricant oils (Markiewicz et al., 2017; Strömvall et al., 2007) PAH is not mobile, has poor aqueous solubility and has high hydrophobic properties Patel et al., 2020) It tends to have a high affinity towards organic matter and is very persistent in the environment Munz, 2018.) Hence, the concentration of PAH is known to be higher in sediments than in water.

Table 5 presents the list of the PAH-16 with the Swedish guideline values for sediment and contaminated soil together with the guideline values for sediment from the Canadian Council of Ministers of the Environment (CCME) and the Norwegian guidelines. Table 6 contains the list of PAH-16 along with the guideline values from the CCME for freshwater and marine water, and the European Union for surface water/freshwater.

The city of Gothenburg only specifies one type of PAH which is benzo(a)pyrene with an effluent limit of 0.27 µg/L. Benzo(a)pyrene is considered to be a group 1 carcinogenic substance which is a hazard index used by the International Agency for Research on Cancer (IARC) for the most probable carcinogenic to humans.

Table 5: Swedish guideline values of PAH-16 for sediment and soil together with Canadian and Norwegian guidelines for sediment. (Naturvårdsverket, 2022; Josefsson, 2017; CCME, 1999; Miljødirektoratet, 2020)

	PAH	Swedish soil* [µg /kg]		Swedish guideline value for sediment* [µg /kg TS]					CCME** [µg/kg		Norwegian guideline value *** [µg/kg TS]				
		SLU	LSLU	Class 1	Class 2	Class 3	Class 4	Class 5	ISQG/ TEL	PEL	Class 1	Class 2	Class 3	Class 4	Class 5
PAH-L	Naphthalene	-	-		<4.9	19	63	≥63	34.6	391	2	27	1754	8 769	>8 769
	Acenaphthylene	-	-	-	-	-	-	-	5.87	128	1.6	33	85	8 500	>8 500
	Acenaphthene	-	-	<5.5			33	≥33	6.71	88.9	2.4	96	195	19 500	>19 500
PAH-M	Fluorene	-	-	<2		9.4	35	≥35	21.2	144	6.8	150	694	34 700	>34 700
	Phenanthrene	-	-	7	17	50	150	≥150	86.7	544	6.8	780	2 500	25 000	>2 500
	Anthracene	-	-	<1	3.1	11	45	≥45	46.9	245	1.2	4.8	30	295	>295
	Fluoranthene	-	-	<18	45	140	390	390	113	1 494	8	400	400	2 000	>2 000
	Pyrene	-	-	<12	30	100	380	≥380	153	1 398	5.2	84	840	8 400	>8 400
PAH-H	Benz(a)anthracene	-	-	<7.5	19	62	180	≥180	74.8	693	3.6	60	501	50 100	>50 100
	Chrysene	-	-	<11	26	67	200	≥200	108	846	4.4	280	280	2 800	>2 800
	Benzo(a)pyrene	-	-	<12	31	99	240	≥240	88.8	763	6	183	230	13 100	>13 100
	Dibenz(a,h)anthracene	-	-	<4.4	8.9	27	79	≥79	6.22	135	12	27	273	2 730	>2730
	Benz(b)fluoranthene	-	-	<32	69	200	440	≥440	-	-	90	140	140	10 600	>10 600
	Benz(k)fluoranthene	-	-	<11	28	79	180	≥180	-	-	90	135	135	7 400	>7 400
	Benzo(ghi)perylene	-	-	<22	62	180	400	≥400	-	-	18	84	84	1 400	>1 400
	Indeno(123cd) pyrene	-	-	<22	62	180	400	≥400	-	-	20	63	63	2 300	>2 300
	PAH 16	-	-	-	-	-	-	-	-	-	300	2 000	6 000	20 000	>2 000
	PAH-L	3	15	<24	76	220	530	530	-	-	-	-	-	-	-
	PAH-M	3.5	20	<57	110	320	1 700	1 700	-	-	-	-	-	-	-
	PAH-H	1	10	<180	320	540	2 600	2 600	-	-	-	-	-	-	-

*SLU=sensitive land use; LSLU=less sensitive land use; Swedish guideline: Class1=very low content; Class 2= low content; Class 3=medium content; Class 4=high content; Class 5=very high content.

**ISQG/TEL=interim marine sediment quality guidelines/threshold effect levels, < TEL= adverse effects rarely occur; PEL=probable effect level, < PEL = adverse effects occasionally occur; > PEL= adverse effects frequently occur.

***Norwegian guideline: Class 1=background levels; Class 2=no toxic effects; Class 3=toxic effects following chronic exposure; Class 4=toxic effects following short term exposure; Class 5 = severe acute toxic effects.

Table 6: Guideline values of PAH -16 from Canadian guidelines for freshwater and the European Union for surface water (CCME, 2010; European Communities, 2008)

PAH	CCME [µg/L]	EU MAC surface water [µg/L]
Naphthalene	1.1	-
Acenaphthylene	-	-
Acenaphthene	5.8	-
Fluorene	3.0	-
Phenanthrene	0.4	-
Anthracene	0.012	0.4
Fluoranthene	0.04	1
Pyrene	0.02	-
Benz(a)anthracene	0.018	-
Chrysene	-	-
Benzo(a)pyrene	0.015	0.1
Dibenz(a,h)anthracene	-	-
Benz(b)fluoranthene	-	-
Benz(k)fluoranthene	-	-
Benzo(ghi)perylene	-	-
Indeno(123cd) pyrene	-	-

MAC=maximum allowable concentration

2.5 Leaching of pollutants

Leaching or washing in chemistry is a process in which a solvent (leaching agent) is used to extract solute from one or more components of a solid particle (Ford, 2022). In other words, it is a process of liquid (solvent) dissolving and removing substances from a solid mixture by leaving other components of the solid undissolved. Sediment washing is a technique where pollutants are removed from sediments by washing with water (Löser et al., 2006; Rulkens, 2005). Leaching agents such as inorganic acids, organic and chelating agents are commonly used to enhance the leaching process for the removal of metals and other organic compounds in sediments (Di Palma & Mecozzi, 2007). However, these leaching agents could potentially have a negative effect when released into the environment. Therefore, it is essential to develop an eco-friendly leaching agent that is non-toxic for sediment washing (Akcil et al., 2015). Soap (saponified tall oil) was proven to be an efficient, biodegradable leaching agent for sediment washing with low environmental impact (Norén et al., 2021). For this reason, soap was chosen as a leaching agent for this work.

Soap is a water-soluble organic component and has hydrophobic and hydrophilic properties. The difference between liquid and hard soap is that liquid soap is made up of fat and potassium hydroxide while hard soap is made up of fat and sodium hydroxide. A compound like soap with hydrophobic and hydrophilic properties could potentially bind to TBT which is hydrophobic and could extract TBT from sediments into a water phase (Norén et al., 2021). Tall oil (pine oil) is a yellow liquid that is a by-product of wood (pine) pulp production. It is a mixture of 30% to 60% saponified fatty acids, 40%

to 60% resin acids, and 5% to 10% unsaponifiable (Bajpai, 2018). Tall oil is extracted from black liquor that comes from the wood pulping process (Foran, 2006). The refined product of tall oil is used for commercial purposes such as liquid soap (saponified tall oil), rosin, etc. In Sweden, the yellow liquid is a frequently used detergent soap, and it is sometimes dyed into green.

2.6 Photoelctrocatalysis (PEC)

Photoelectrocatalysis (PEC) is a known method in wastewater treatment but is less commonly associated with sediment treatment. Therefore, it is of interest to leach out pollutants into the water phase from pollutant sediment by washing and treating the sediment leachate water using the PEC method.

PEC degradation is a multifaceted process that is governed by several variables, such as electrode and catalyst materials, light intensity and wavelength, as well as electric current and voltage. It is a method that integrates photocatalysis and electrocatalysis technology that simplifies the photocatalytic process (Garcia-Segura & Brillas, 2017). The increasing prevalence of coexisting organic pollutants and metals has led to a growing interest in the simultaneous removal of both pollutants using PEC (Mao et al., 2020; Ye et al., 2021). PEC technique involves using a semiconductor photoanode exposed to light energy equal to or greater than its band gap. During this process, an electron is expelled from the semiconductor's valence band to its conductive band, resulting in the formation of a positively charged vacancy (Coha et al., 2021). PEC then utilizes this charge separation to enhance the breakdown of organic pollutants in contaminated water (Garcia-Segura & Brillas, 2017). PEC, using materials like titanium dioxide (TiO_2), accelerates slow chemical reactions. TiO_2 particles, when exposed to light, generate highly oxidizing holes and hydroxyl radicals from water. Photoelectrons from TiO_2 reduce oxygen to superoxide. Doping TiO_2 with transition metals expands its visible light activity (Kurzweil, 2023). Titanium dioxide photocatalysis kills bacteria and other microorganisms. Bacteria are made up of organic compounds, and therefore enhance the degradation of organic pollutants. Additionally, its availability, cost-effectiveness, and chemical stability make TiO_2 a preferred photocatalyst. The electrochemical part can remove metals from contaminated water. During the process, photoelectrons can reduce metal ions to their elemental forms and get deposited on the cathode surface (Ye et al., 2021).

3 Materials and method

This chapter consists of the second part of the thesis describing the sampling sites, the collection and preparation of the samples, the characterization and classification of samples, and the laboratory experiments.

3.1 Sampling sites

To investigate how dredged sediment from a marina and sediment from traffic runoff differ from each other, two different sampling sites were selected in Gothenburg, Sweden. A marina sediment sample was collected from one of Sweden's oldest marinas on the west coast. The area is also famous for its swimming spot that is used for recreational purposes among the locals. It is possible that this marina sediment shares similar characteristics with sediments from other marinas. The other sample is a stormwater traffic runoff sediment that was collected from an underground sediment chamber in Gårda, a district in Gothenburg, Sweden. The area consists of a highway and small streets with an average daily traffic of 85 700 vehicles (Björklund et al., 2008). The traffic runoff is discharged into a stormwater system where it flows through seven underground sediment chambers. The marina samples were analyzed for metals and TBT, and stormwater traffic runoff sediment samples for metals and PAH.

3.2 Collection and Preparation of samples

Sediment samples were collected using a grab sampler from a stormwater drainage system at Gårda and a marina at Gothenburg. The sediment samples were then stored in a refrigerator at 4°C. Once the leaching process was done, the samples that is the leachate water and the sediment were stored in different containers. A dark glass bottle of 1L was to be used for PAH analysis, a 500 ml clear plastic bottle for TBT analysis, and a 100 ml plastic bottle for metal analysis for storage of leachate water samples in a refrigerator at 4°C until they were sent for chemical analysis. Furthermore, a glass container for PAH and TBT analysis and a plastic container for metal analysis were to be used for storage of sediment samples in a refrigerator at 4°C until they were sent for chemical analysis. The selection of bottles and containers for sample storage was done to avoid the degradation or vaporization of nutrients and organic substances.

3.3 Characterization and classification of samples.

All original sediment samples before the leaching process were measured for dry weight and Loss of ignition (LOI) analysis by heating at 105°C in an oven and 550°C in a furnace respectively, following the standardized method SS 02 81 13. In this study, eight toxic metals namely As, Pb, Cd, Cr, Hg, Ni, Cu and Zn were the main focus for metal analysis, PAH-16 that were listed in chapter 1.2.4 and organotins were analyzed in water and sediment samples. The marina sample was chemically analyzed for organotin and toxic metals while the traffic runoff sediment sample from Gårda was analyzed for PAH and toxic metals.

The characterization of the samples was mainly focused on the original sediment samples to use as a point of reference and evaluation to see if risk class reduction is possible for the sediments after leaching. Additionally, the guideline values for surface water were also used to check the level of contamination of the leachate water. Therefore, a description of sediments after leaching and leachate water characterization will not be presented in the results. The guideline values can be found from Table 1 to Table 9.

The sediment samples were compared with Swedish, Canadian, and Norwegian guideline values and risk classes. The leachate water samples for metals were compared with Gothenburg City for effluent water and the Swedish EPA for lakes and watercourses risk classes. Since there are no guideline values available in the Swedish EPA for OTCs and PAH for surface water, although it exists for groundwater, the comparison was made using the Gothenburg City guideline of effluent polluted water, the Canadian guideline for freshwater/marine water, and the European guideline for surface water. All guideline values do not indicate the mobility of a contaminant but rather are reference values.

3.4 Laboratory Experiment

The laboratory experiments were divided into two parts: a leaching process that constitutes three phases followed by PEC analysis in the third phase. The three leaching phases included:

- Phase 1 utilizing different soap concentrations as a leaching agent and was subjected to 2 hours and 24 hours of shaking time to check the optimum shaking time and used distilled water as liquid.
- Phase 2 using Milli-Q water as a liquid. Soap and methanol (to enhance organic pollutants leaching) were used individually and in combination.
- Phase 3 used Milli-Q water as liquid and was a double leaching method meaning the sediments were washed twice using Milli-Q water and Methanol and leaching agent.

In Phase 2 and Phase 3, pH was reduced to 3 using nitric acid to enhance metals leaching on selected samples, and the samples were subjected to 24 hours of shaking time in both phases. The different leaching processes were built to determine the optimal concentration of leaching agent for the removal of both metals and organic pollutants. The Leaching process and PCE analysis were conducted at the Water and Environmental (WET) Laboratory at Chalmers University of Technology.

A detergent soap was used as a leaching agent since it was considered to have a low environmental impact (Norén et al., 2021). An ordinary store-bought detergent from the brand Grumme, the yellow based tall oil, was chosen since store-bought detergents are environmentally friendly and easily accessible.

3.4.1 Leaching Process Phase 1

For the first phase of the leaching process, three soap concentrations 1.5 ml, 15 ml, and 150 ml were considered to determine the optimal concentration. The marina sediment and the traffic runoff sediment having a dry weight of 150 g were mixed with each soap concentration at a liquid/solid (L/S) ratio of 10. Distilled water was used as liquid for dilution taking into consideration that it is easily accessible. Each soap concentration has two samples that were placed on a shaking table for 24 hours and 2 hours at a speed of 150 rpm. The purpose of this was to determine the optimal leaching time. The samples were left to get settled in 3 hours. The leachate water samples were drawn out using a pipette and the settled particles (sediments) were then collected separately. The water samples and the sediment samples were stored in a refrigerator at 4°C until analysis. Table 7 below contains Phase 1 leaching process sample lists. It is to be noted that sediment samples SM1.2.2, a 15 ml soap concentration with 24 hours shaking time and SM1.3.2, a 150 ml soap concentration with 24 hours shaking time were sent for analysis on account of project budgeting.

Table 7: Phase 1 leaching process sample lists.

S.no	Sample name	Sample sites	Volume of leaching agent [ml]	Shaking time [hrs]
1	SM1-1.5.2	Marina	1.5	2
2	SM1-1.5.24	Marina	1.5	24
3	SM1.15.2	Marina	15	2
4	SM1.15.24	Marina	15	24
5	SM1.150.2	Marina	150	2
6	SM1.150.24	Marina	150	24
7	SG1-1.5.2	Gårda	1.5	2
8	SG1-1.5.24	Gårda	1.5	24
9	SG1.15.2	Gårda	15	2
10	SG1.15.24	Gårda	15	24
11	SG1.150.2	Gårda	150	2
12	SG1.150.24	Gårda	150	24

*All experiments were done using L/S =10 and soap as leaching agent.

3.4.2 Leaching Process Phase 2

The second phase of the leaching process proceeded after determining the optimal concentration of soap and the leaching time. Three different sampling approaches were used for both the marine and traffic runoff sediments samples having a dry weight of 150 g while keeping the L/S ratio at 10 and shaking time as 24 hours at a speed of 150 rpm for all samples. In the first approach, the sediment samples were mixed by using 150 ml of soap as the leaching agent and mixed with 150 ml solvent of 99% methanol to enhance the leaching of organic pollutants. Milli-Q water was used as liquid for dilution. The solvent was calculated as a liquid by keeping L/S ratio of 10. Nitric acid was used to lower the pH to 3. In the second approach, only Milli-Q water and methanol of 150 ml were used as leaching agents without adding soap. pH was reduced to 3 by using nitric acid. pH was reduced to possibly enhance the release of metals from sediment. The third approach used just Milli-Q water as a leaching agent without altering pH. The samples were then placed on a shaking table for 24 hours at a speed of 150 rpm. The samples were left to get settled for 3 hours. The leachate water samples were drawn out using a pipette and the settled particles (sediments) were then collected separately. The water and sediment samples were stored in a refrigerator at 4°C until analysis. Table 8 below contains Phase 2 leaching process sample lists.

Table 8: Phase 2 leaching process sample lists.

S. No	Sample name	Sample sites	Volume of leaching agent [ml]	pH reduced to 3
1	SM2. 150.S+Me	Marina	Soap = 150. Methanol = 150	Yes.
2	SM2. 150.Me	Marina	Methanol = 150	Yes
3	SM2.MQ	Marina	Milli-Q water	No
4	SG2. 150.S+Me	Gårda	Soap = 150. Methanol= 150	Yes
5	SG2. 150.Me	Gårda	Methanol = 150	Yes
6	SG2.MQ	Gårda	Milli-Q water	No

*All experiments were done using L/S = 10, 24 hours of shaking and milli-Q water as liquid.

3.4.3 Leaching Process Phase 3

The third phase of the leaching process was conducted based on the second phase analysis. The shaking time for all samples is 24 hours at a speed of 150 rpm. This phase involved two leaching steps (double shaking and leaching) for both the marine and traffic runoff samples. The first step followed the leaching processes in Phase 2, utilizing Milli-Q water as the leaching agent with an L/S ratio of 10 with a dry weight of 150 g. The samples were shaken for 24 hours and allowed to settle for 3 hours. The leachate water samples were drawn out using a pipette and the settled particles (sediments) were then collected separately. The drawn-out water samples were stored in a refrigerator at 4°C for further chemical analysis and also for the treatment of PEC.

In the second step, the remaining sediment residue from the first step was subjected to an additional leaching process. Taken into consideration that some particles were removed from the first step, the L/S ratio was recalculated to11. Milli-Q water was used as liquid and mixed with 150 ml solvent of 99% methanol to enhance organic pollutants' leachability. The solvent was calculated as a liquid by keeping an L/S ratio of 11. Nitric acid was to lower the pH to 3 to increase the leachability of metal. The samples were shaken for 24 hours, followed by a 3-hour settling period hours. The leachate water samples were drawn out using a pipette and the settled particles (sediments) were then collected separately. The water and sediment samples were stored in a refrigerator at 4°C for further chemical analysis and also for the treatment of PEC. Table 9 below contains Phase 3 leaching process sample lists.

Table 9: Phase 3 leaching process sample.

S. No	Step	Sample name	Sample sites	Volume of leaching agent [ml]	L/S ratio	pH reduced to 3
1	1	SM3.MQ_S1	Marina	Milli-Q water	10	No
2	2	SM3.150.Me_S2	Marina	Methanol = 150	11	Yes
3	1	SG3.MQ_S1	Gårda	Milli-Q water	10	No
4	2	SG3.150.Me_S2	Gårda	Methanol = 150	11	Yes

*All experiments were done using Milli-Q water as liquid and 24 hours of shaking

3.4.4 Photoelectrocatalysis (PEC)

The experimental setup for PEC utilized a bench lamp (UVP, AnalytikJEna) equipped with two UV fluorescent tubes (15 W) positioned above it. These tubes emitted light at different wavelengths: 365 nm (UVA), 302 nm (UVB), or 254 nm (UVC). To measure the intensity of light from the fluorescent tubes, Extech UVA/UVC light meters and IM-213 UV-AB meters were employed. In this study, a TiO_2 photocatalysis plate served as the cathode, while titanium was used as the anode. TiO_2 was heated to a semi-molten state and sprayed onto a metal surface, where the particles adhered, forming a photocatalytic surface.

This treatment utilized leachate water sourced from Phase 3 that involved two leaching steps. Two different-sized beakers were utilized: a 230 mm diameter beaker for traffic runoff samples (for analyzing PAH and metals) and a 130 mm diameter beaker for marina samples (for analyzing TBT and metals). A bigger beaker was used for the traffic runoff samples since it has larger quantity of 1L, while the marina samples have smaller quantity of 500 ml. Electrodes were affixed to the beakers and placed beneath the two UV fluorescent tubes to undergo PEC, see Figure 2. Additionally, an electrolyte solution of NaCl at a concentration of 5.8 g/L was added to facilitate electrical conductivity in the samples. The samples were subjected to PEC treatment for a duration of 72 hours. Next, the water samples were then stored in a refrigerator at 4°C until further analysis. Table 10 below contains PEC analysis sample lists.

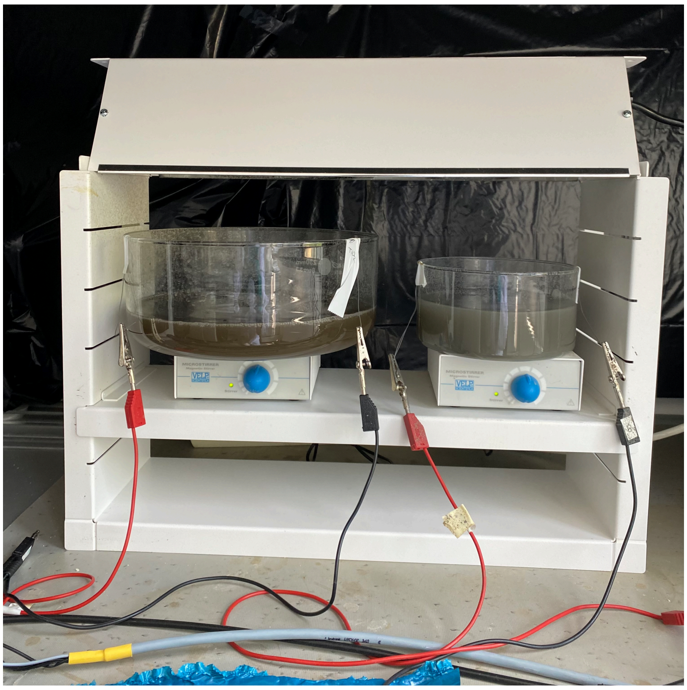

Figure 2: PEC set up

Table 10: PEC sample lists and descriptions

S.No	Sample site	Sample names
1	Marina	SM3.MQ_S1_PEC
2	Marina	SM3. 150.Me_S2_PEC
3	Gårda	SG3.MQ_S1_PEC
4	Gårda	SG3. 150.Me_S2

4 Chemical analysis

After each leaching process phase and PEC, the sediment samples and the leachate water samples were chemically analysed at ALS Scandinavia AB for metals, OTCs and PAH. Table 11 presents the standards and analysis methods used for analysing sediment and leachate water for different parameters.

Table 11: Standards and methods used for analysing different parameters.

Sample	Parameter	Standard	Method
Sediment	Metal	SS-EN ISO 17294-2:2016; US EPA 200.8:1994	ICP-SFMS
	Organotin	SE-SOP-0036 (SS-EN 1SO 23161–2028)	GC-ICP-MS
	PAH	SPINTABs: SIS/TK 535 N012	GS-MS
Water	Metal	SS-EN ISO 17294-2:2016; US EPA 200.8:1994	ICP -SFMS
	Organotin	E-SOP-0037 (ISO 17353:2005)	GC-ICP-MS
	PAH	US EPA 8270D, US EPA 8082A, CSN EN ISO 6468 and US EPA 8000D	GC-MS or GC-MS/MS.

5 Results and Discussion

In this chapter, the results for the marina and traffic runoff original sediments, and sediments post-leaching from three leaching processes: Phase 1, Phase 2, Phase 3, and PEC are presented and discussed. The original results from the chemical analysis of metals, OTCs and PAH–16 from the commercial laboratory can be found in Appendix E to H.

5.1 Original sediment

This section presents the characteristics of the original sediment sample meaning the sample before the leaching processes for both marina and traffic runoff sediments. Focus was made on eight metal elements viz. As, Cd, Cr, Hg, Ni, Pb, Cu, and Zn which were specified on the guideline's values report. Organic pollutants namely TBT in the marina sediment andPAH-16 in the traffic runoff were the main point of interest. This PAH-16 comprises PAH-L, PAH-M, and PAH-H which were categorized in Sweden based on their physical-chemical attributes and levels of toxicity.

5.1.1 Marina sample

The concentrations of all metals and organotin compounds (OTCs) for the marina sediment samples are presented in Appendix A, Table A.1. In the marina original sediment, a Zn concentration of 11 800 mg/kg and Cu of 18 900 mg/kg were the highest of the metals analyzed. Since Cu and Zn are used as a constituent in antifouling paint for boats/ships they were expected to be found in the marine sediment. When the original marina sediment sample is compared with the Swedish soil guideline values for As, Pb, Cd, Cu, Hg, and Zn the concentrations were higher than the Swedish guidelines for contaminated soil for sensitive land use (SLU), except for Cr and Ni. For soil in less sensitive land use (LSLU), Cu and Zn were higher than the guideline values. However, this comparison may be considered not to be completely definite since the guideline value is for soil. Swedish sediment guideline values for metals are not available, therefore Canadian and Norwegian guideline values are used. According to the Canadian guideline, Cu, Hg, Pb, and Zn were higher than the probable effect level, and hence adverse effects on the aquatic ecosystem will frequently occur, which means the marine environment is affected. The remaining metals were either below the limits or at a point where effects would rarely occur. According to the Norwegian guidelines, Cu, Hg, and Zn are classified as Class 5 category meaning that severe acute toxic effects will occur in the aquatic environment. The other metals were classified as background values or to have nontoxic effects and therefore will cause no harm to the aquatic environment.

The concentration of TBT in the original sediment sample was 58 000 μg/kg, DBT 5 700 μg/kg, and MBT 1 670 μg/kg. All organotins had a very high concentration in the sediment. The concentrations of TBT, DBT and MBT were higher than the Swedish contaminated soil guideline for both sensitive land use and less sensitive land use in the original marina sample. According to Swedish sediment guidelines, all organotin had a very high concentration and are classified as Class 5 risk class. Only TBT is available in the Norwegian guidelines. According to the Norwegian guidelines, the TBT concentration before leaching was a Class 5 category of risk class, and hence severe acute toxic effects will occur on the aquatic environment. After more than two decades of TBT banned in Sweden, the results indicates that the concentration of TBT > DBT

> MBT (high to low). This shows the slow degradation process and persistency of TBT in sediments.

The concentrations of TBT, Cu, Zn, and Hg in the original marine sediment are very high and these metals are of the highest concern for the marine environment. Cu and Zn are commonly used as a replacement for TBT as an antifouling agent for boats/ships and therefore the result seems only reasonable. This can further be corroborated by another study that conducted a similar analysis on marine sediment in Gothenburg Sweden and found similar results (Norén et al., 2021). To further apprehend the environmental risk associated with Hg, further investigation such as geochemistry investigation of Hg in water sediments, evaluation of its source and pathway will be of interest.

5.1.2 Traffic runoff sample

The concentration of metals and PAH for the original traffic runoff sediment are presented in Appendix A, Table A.2. The concentrations of Zn (537 mg/kg) and Cu (110 mg/kg) were the highest concentrations of the metals analysed. This was expected since traffic runoff has high concentrations of these metals (Legret & Pagotto, 1999; Mangani et al., 2004). However, the concentration is much lower than in the marina sample showing the importance to reduce the emission from antifouling paints. Copper and Zinc were higher than the Swedish guideline values for contaminated soils for sensitive land use, and Zn was higher than the guideline for less sensitive land use. The other measured metals are below sensitive land use or less sensitive land use. As stated previously in Section 5.1.1, this comparison may be considered not to be completely definite since the guideline value is for soil. According to the Canadian guidelines, most metals were below the threshold effect levels, and adverse effects will rarely occur, but exposure to Cu will cause occasional adverse effects on the aquatic environment, and exposure to Zn will cause frequent adverse effects on the aquatic environment. According to the Norwegian guidelines, the metals of concern are Cu and Zn. The exposure to Zn will cause toxic effects on the aquatic environment upon chronic exposure, a class 3 risk level and short-term exposure to Cu will cause toxic effects, a class 4 risk level. The other remaining metals are classified as background values or have nontoxic effects and therefore will cause no harm to the environment.

In the original traffic runoff sediment sample, the highest concentrations of specific PAH are pyrene and fluoranthene with concentrations of 1100 µg/kg and 556 µg/kg respectively. These two PAHs have a medium molecular weight and fluoranthene is considered an indicator of dangerous PAH (European Communities, 2008.). A total of 4 310 µg/kg of PAH-16 was quantified in the original traffic runoff sediment. To be specific, 90 µg/kg of PAH-L, 2 190 µg/kg of PAH-M, and 2 040 µg/kg of PAH-H were found. A high concentration of PAH-M and PAH-H is expected since both PAH-M PAH-H is commonly from rubber tires and from combustion engines(Markiewicz et al., 2017). All PAH-L, PAH-M, and PAH-H considerably exceeded the Swedish guideline for contaminated soil for sensitive land use and less sensitive land use. According to the Swedish guideline value for sediment, PAH-M and PAH-H have a very high content and high content that are classified as Class 5 and Class 4 risk classes respectively. According to the Canadian guideline, naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, fluoranthene, pyrene, benz(a)anthracene, chrysene, benzo(a)pyrene and dibenz(a, h)perylene are at the probable effect level and therefore adverse effects on the aquatic environment will occasionally occur. According to the Norwegian guidelines, short-term exposure to pyrene, chrysene, benz(b)fluoranthene, benz(k)fluoranthene, benzo(a)pyrene, indeno(123cd)pyrene, benzo(ghi)perylene are the main concerned which will cause toxic effects on the aquatic environment and is classified as Class 4 risk class. Additionally, exposure to naphthalene, anthracene, fluoranthene, benz(a)anthracene, and dibenz(a, h)anthracene will also cause toxic effects following chronic exposure in the aquatic environment which is classified as Class 3 risk class.

The major environmental risk concern for PAH-16 is PAH-M specifically phenanthrene, fluoranthene and pyrene which occurred in the highest concentration, and benzo(a)pyrene is of interest for PAH-H which is a big carcinogenic indicator by the International Agency for Research on Cancer (IARC). Similarly, the metals with the highest environmental concern are Cu and Zn. The results observed here is reasonable since Cu, Zn and PAH are the main pollution release from wear/tear of road, tires, and vehicle combustion (Legret & Pagotto, 1999; Mangani et al., 2004; Markiewicz et al., 2017). Further investigation such as the mobility of these pollutants will be of interest.

5.2 Sediment after leaching

This section presents the results and discussion of the marina and traffic runoff sediment post three leaching phases; Phase 1 involved utilizing distilled water as liquid and soap as a leaching agent with a concentration of 15 ml, 15 ml and 150 ml by subjecting to 2 hours and 24 hours of shaking time. Phase 2 involved using Milli-Q water as liquid, soap, methanol and Milli-Q water as leaching agents in combination and individually. Phase 3 also used Milli-Q water as liquid and was a double leaching method: first with only Milli-Q water and the second with a combination of 150 ml methanol and 150 ml Milli-Q water.

For all leaching processes, selected pollutants in accordance with the original sediment results are presented. In the marina sediment, the focus was on Cu, Zn and TBT. In the traffic runoff sample, pollutants such as Cu, Zn, and the total of PAH 16 were of interest. The detailed concentration of all metals, OTCs and specific PAH-16 are presented in Appendix A to D for all the three leaching phases.

5.2.1 Metals

Figure 3 presents the Cu concentrations in the marina sediments after the leaching processes. The results of the leaching experiment reveal significant variations in the Cu concentration across different phases of the process. In Phase 1, represented by samples SM1.15.24 (150 ml soap with 24 hours shaking) and SM1.150.24 (150 ml soap with 24 hours shaking) the Cu concentration was 21 800 mg/kg and 18 600 mg/kg, respectively. In Phase 2, samples SM2.150.S+Me (150 ml soap and 150 methanol), SM2.150.Me (150 ml methanol), and SM2.MQ (only Milli-Q water) had after leaching a Cu concentration of 19 200 mg/kg, 18 300 mg/kg and 20 500 mg/kg, respectively. Lastly Phase 3 a double leaching method, sample SM3. 150.Me_S2 (step 2, 150 ml methanol) yielded the highest remaining Cu concentration of 23 300 mg/kg. Interestingly, most samples had higher Cu concentrations compared to the original sample, which had 18 900 mg/kg of copper.

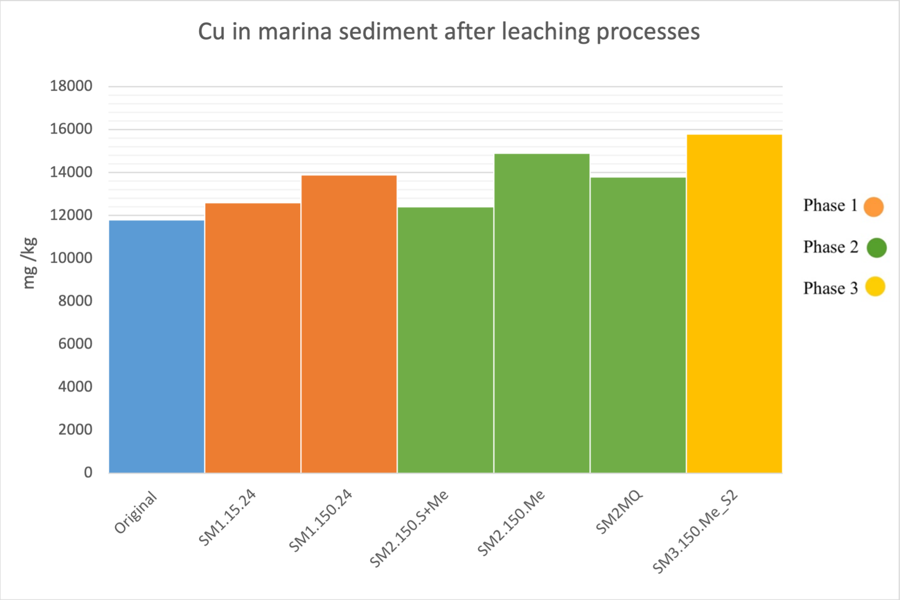

Figure 3: Concentration of Cu in marina sediment after leaching

Figure 4 illustrates the Zn concentrations in marina sediments post-leaching, showing a trend like Cu. In all three phases, the concentrations of Zn increased after leaching. The concentration after leaching ranged from 12 400 mg/kg to 15 800 mg/kg while, while the original sample contained 11 800 mg/kg of Zn. The highest concentration of Zn was observed in Phase 3 with a concentration of 15 800 mg/kg.

This increase in concentration of Cu and Zn was not expected especially in Phase 3 after double leaching. The explanation for this is not totally clear, but one reason could be that small particles in the sediment dissolve into the liquid during washing and therefore the total concentrations of all pollutants that are not released increase in the sediments after washing, which was confirmed in the study by Norén et al., (2021). Another possible reason can be that metal elements are hard bound to the sediments e.g., in paint flakes and after double shaking, they are more available for chemical analysis.

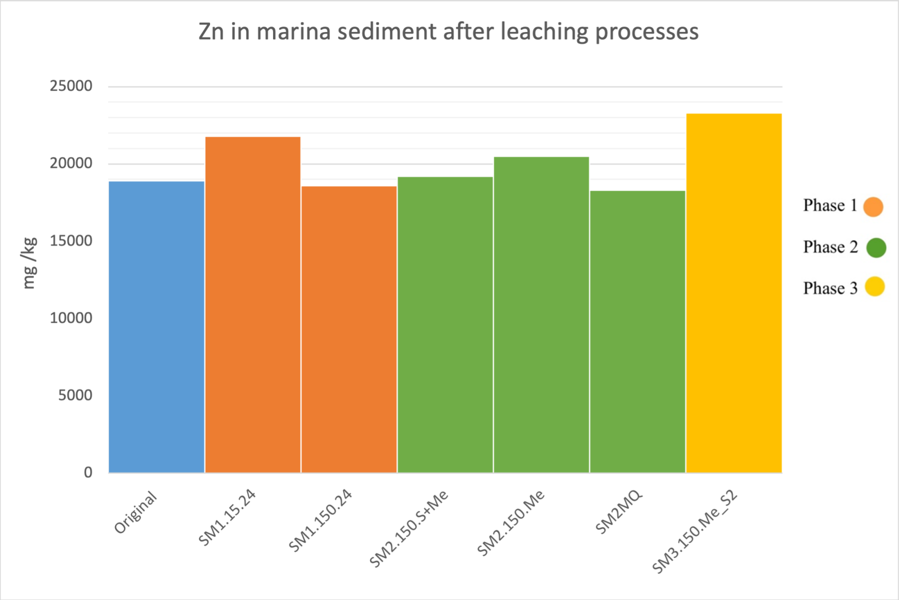

Figure 4: Concentration of Zn in marina sediment after leaching

In Figure 5, the concentration of Cu is shown in traffic runoff sediment after leaching. The Cu concentration prior to leaching was 110 mg/kg. In Phase 1, it was observed that sample SG1.150.24 which was subjected to 24 hours of shaking with 150 ml soap had a 27% reduction of Cu whereas SG1.15.24 which was subjected to 24 hours of shaking with 15 ml soap had an increase of 9%. In Phase 2, SG2.150.S+Me which was subjected to 24 hours of shaking with 150 ml soap together with 150 ml methanol and SG2.MQ which was subjected to 24 hours of shaking with only Milli-Q water had a Cu reduction of 14% and 11% respectively, while SG2.150.Me that was subjected to 24 hours shaking with 150 methanol showed an increase of approximately 2%. In Phase 3, sample SG3.150.Me_S2 that was subjected to double leaching steps and 24 hours shaking, first with just Milli-Q water followed by 150 ml methanol had a 3% reduction of Cu.

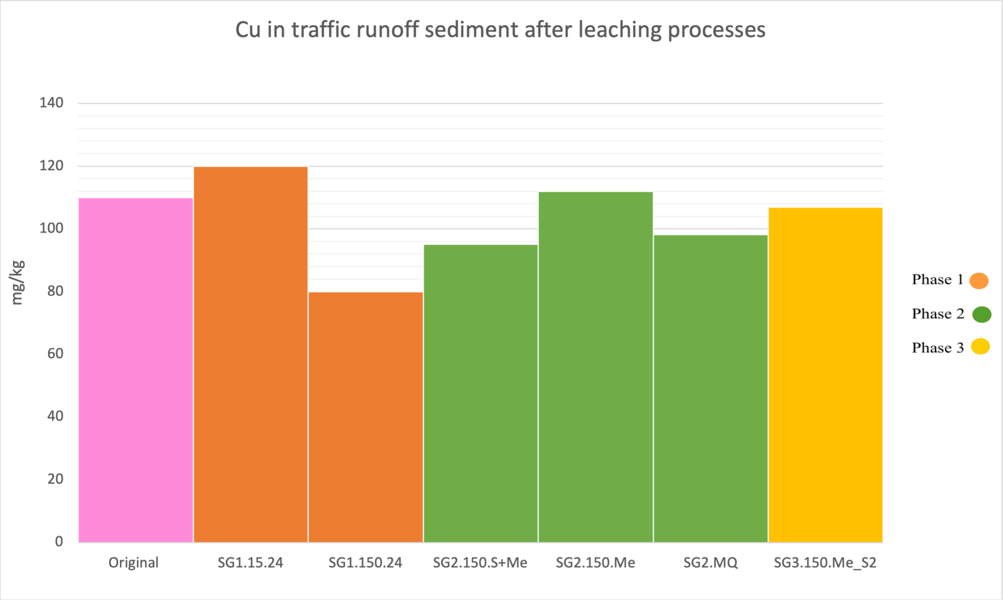

Figure 5: Concentration of Cu in traffic runoff sediment after leaching

Figure 6 presents the Zn concentration in the traffic runoff sediment after undergoing leaching processes. The concentration of Zn in the original sample was 537 mg/kg. Most of the Zn concentration is reduced to a certain extent in this sediment, except for sample SG1.15.24 in Phase 1 which had an increase of 10%. In Phase 1, sample SG11.150.24, which was subjected to 24 hours of shaking with 150 ml soap as a leaching agent had approximately 12% reduction of Zn. In Phase 2, sample SG2.150.S+Me, a sample that was subjected to 24 hours of shaking with 150 ml soap and 150 ml methanol as a leaching agent yielded a reduction of approximately 27%. Sample SG2.MQ, which was subjected to 24 hours of shaking with Milli-Q water, had a 20% reduction of Zn. Lastly in Phase 3, sample SG3.150.Me_S2 that was subjected to double leaching steps and 24 hours of shaking, first with just Milli-Q water followed by 150 ml methanol had a Zn reduction of about 28%.

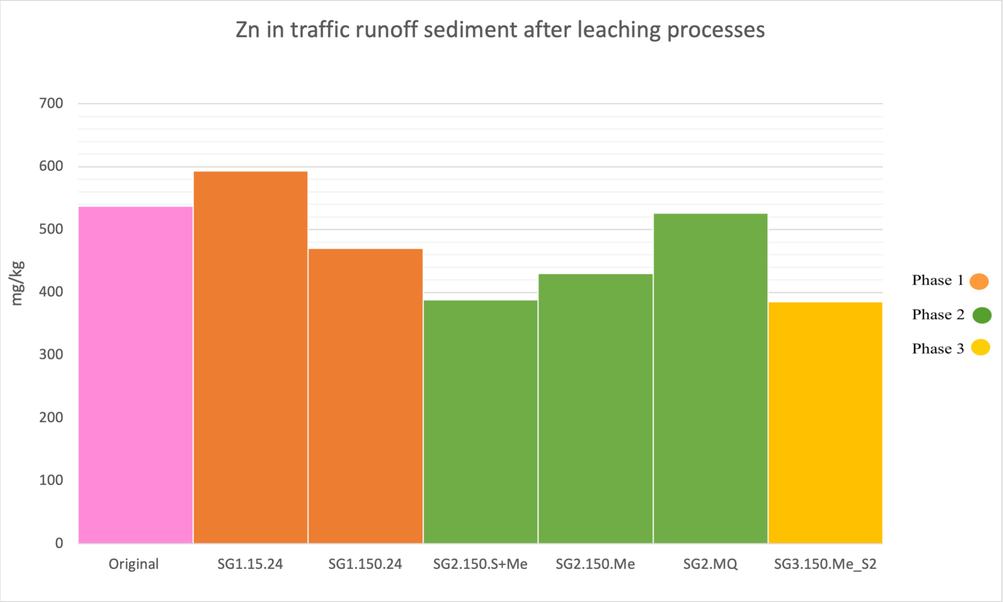

Figure 6: Concentration of Zn in traffic runoff sediment after leaching

The leaching method using different concentrations of soap, methanol and Milli-Q water is not good for the reduction of Cu and Zn in the marina sediment. However, it is possible to some extent for the traffic runoff sediments using 150 ml soap with 24 hours shaking time that yielded the best reduction of 28% Cu. Additionally, the traffic runoff sample that was subjected to 24 hours of shaking with 150 ml soap and 150 ml methanol as a leaching agent yielded the best reduction of 27% Zn. This suggests that the leaching process is effective in drawing the metal ions toward the carboxylic ion (R–COO$^-$) group molecules present in the soap (Norén et al., 2021). This also indicates the complexity and the distinctive characteristics between the two types of sediment. Additionally, the comparison between these two sediments cannot be made. This is because the toxic metals are strongly bound to the marina sediment, often in the form of paint flakes and the sediments exhibit different characteristics. For instance, the marina sediment has more salt content than the traffic runoff sediment, and the differences in their physical appearance of particle size. It is also to note that the double leaching method yields a reduction of 27% in Zn, but Cu reduction is very small. An additional treatment method is needed to remove metals in the marina and traffic runoff sediment to achieve satisfactory removal efficiency. It should also be noted that the reduction observed in traffic runoff sediment is not efficient enough to reduce the risk class.

5.2.2 Organic pollutants

Figure 7 presents the result of TBT concentration in the marina sediment after the different leaching processes. The concentration of TBT in the original sediment was as high as 58 000 μg/kg. The results showed that in Phase 1 the TBT in the remaining sediments increased when the leaching was conducted using soap. This was unexpected since previous studies showed that soap as a leaching agent can reduce TBT (Norén, 2021). The possible reason could be that in an aqueous solution, cationic organotin is considered to be dominant therefore, there may be a complexity in electrostatic interaction during leaching between the organotin-positive ions, and the minerals present in the sediment (De Carvalho Oliveira & Santelli, 2010). Additionally, if organotin compounds occur in positive ions, the interaction between the positive ions and the carboxylic group of soap can lead to the formation of complexes that alter the properties of soap, potentially affecting its effectiveness as a leaching agent. (Norén et al., 2021). Another explanation is that TBT occurs in paint flakes which makes it more available for chemical analysis after shaking.

In Phase 2, sample SG2. 150.S+Me was subjected to 24 hours of shaking with 150 ml soap, and 150 ml methanol, which showed an increase in TBT. On the other hand, sample SM2.150.Me that was subjected to 24 hours of shaking with 150 methanol and Milli-Q water had a reduction efficiency of about 70% yielding the best results. SM2.MQ a sample that was subjected to just Milli-Q water had a TBT reduction of approximately 8%. When organotin is mixed with Milli-Q water, it facilitates the scattering/diffusion of TBT which could increase leaching efficiency due to its hydrophobic property meaning low in ion and conductivity (Lindahl et al., 2013). Despite the reduction of TBT by methanol and Milli-Q water, due to its very high content in the original sediment, the risk class cannot be reduced. Further treatment is required to meet the desired environmental quality control.

In Phase 3, it was found that sample SG3. 150.Me_S2 that was subjected to double leaching steps and 24 hours of shaking, first with just Milli-Q water followed by 150 ml methanol had a TBT reduction of about 38%. This indicates the efficiency of double leaching for the removal of TBT. However, this reduction was not as efficient as the sample in Phase 2 SM 2. 150.Me (150 ml methanol+ Milli-Q water) that had a reduction of 70%. To achieve an optimal removal rate, further investigation could be conducted by reversing the order of these two leaching steps.

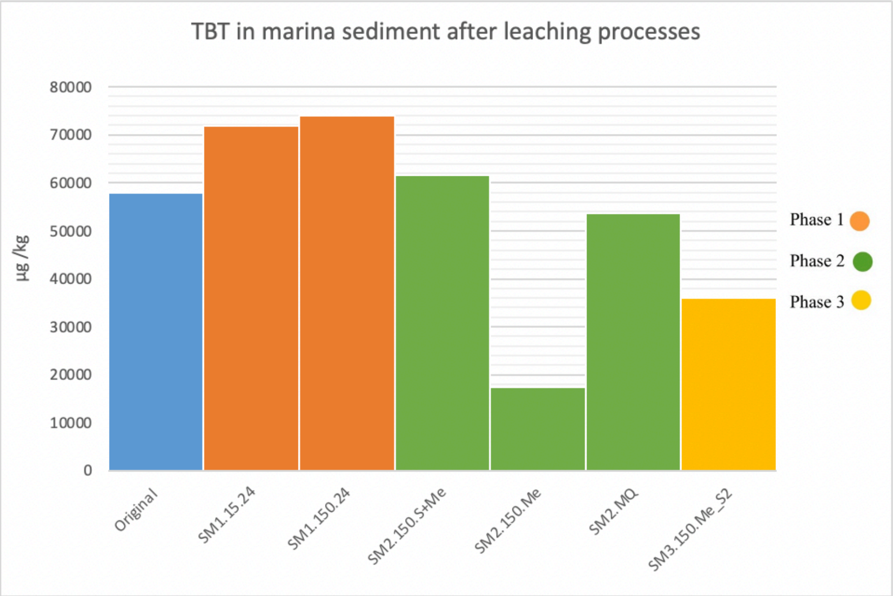

Figure 7: TBT concentration in marina sediment after leaching

In Figure 8, the total concentration of the PAH-16 is presented. The concentration of PAH in the original traffic runoff sediment was 4 310 µg/kg. In Phase 1, it was observed that only sample SG1.15.24, that was subjected to 24 hours leaching with 15 ml soap as leaching agent had a reduction of 25%, whereas sample SG1.150.24 that was subjected to 24 hours shaking with 150 ml soap increased by 24%.

In Phase 2, the sample with a combination of 150 ml soap, 150 ml methanol and Milli-Q (SG2. 150.S. Me) increased the PAH concentration in the sediment indicating that this leaching agent is unsuitable. The sample with 150 ml methanol and Milli-Q water (SG2. 150.Me) reduces the total percentage by about 40% while, the sample using Milli-Q water alone (SG2.MQ) had the highest reduction. 55%. Like TBT, PAH also has a high hydrophobic property which could enhance leaching efficiency when it is mixed with Milli-Q water (Lindahl et al., 2013). However, the reduction of PAH in the sediment is not able to reduce the risk class.

Lastly, in Phase 3, it was observed that after the double leaching (SG 3. 150.Me_S2) which was subjected to double leaching steps and 24 hours of shaking, first with just Milli-Q water followed by 150 ml methanol increased the concentration of PAH by 46%. This was also unexpected since the sample SG2. 150.Me (150 ml methanol + Milli-Q water) in leaching process 2, had a 40% reduction. The explanation for this could be that PAH may be present in flakes or small vehicle rubber wear particles in the sediment. Hence, after continuously double shaking the particles scattered and made more available during chemical analysis.

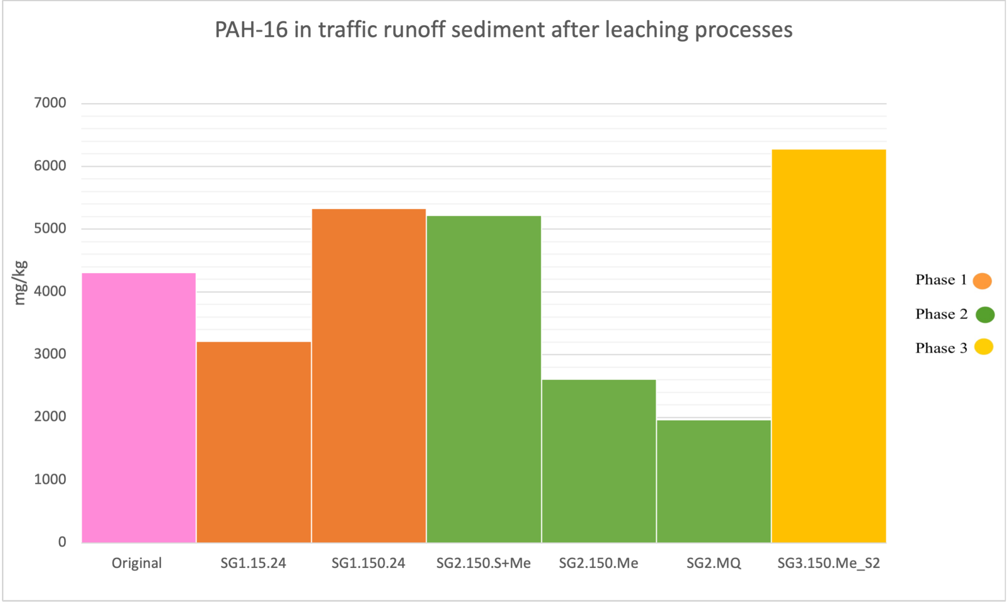

Figure 8: PAH-16 concentration in traffic runoff sediment after leaching

It was observed that a reduction in TBT concentrations in the marina sample by approximately 70% when using a leaching agent consisting of 150 ml methanol, 150ml soap, and Milli-Q water as the liquid. Similarly, a substantial reduction in PAH concentrations, roughly 40%, was also achieved using the same combination of 150 ml methanol, 150 soap, and Milli-Q water. However, the most substantial PAH reduction in traffic runoff sediment occurred totally unexpectedly with Milli-Q water alone as the leaching agent, resulting in a 55% reduction. The double leaching method proves effective for TBT removal, although it may not be the optimal choice. However, it does not yield the same results for PAH, likely because PAH may have existed in rubber particles that caused the particles to disperse and become more accessible during chemical analysis. Additionally, despite the reduction of TBT and PAH concentrations, it is important to note that the risk class, according to the guidelines cannot be lowered.

5.3 Leachate water

This section presents the results and discussion of the leachate water from the three leaching processes. It contains metals specifically Cu, and Zn in the marina and traffic runoff leachate water as well as the results following PEC treatment. In addition to those organic pollutants, particularly TBT in marina sediment and PAH in traffic run-off sediment along with the results after PEC treatment are presented. The aim of PEC was to recover metals and degrade the TBT and PAHs. A comparison is made between the leachate water from Phase 3 and the leachate water after PEC treatment, given that the leachate used for the PEC process originated from Phase 3.

5.3.1 Metals

Figure 9 shows the Cu concentration in marina leachate water. The highest concentration of Cu 11 900 µg/L was found in Phase 1 sample SM1-1.5.24 which was subjected to 24 hours of shaking with 1.5 ml soap. Samples SM1.150.2 and SM1.150.24, both subjected to 150 ml of soap and shaken for 2 hours and 24 hours, respectively, yielded high Cu concentrations. Overall, Phase 1 extracted a higher concentration of Cu into the water phase when compared to Phase 2 and Phase 3. This was not anticipated since Phase 2 and Phase 3 were developed to yield higher Cu concentrations in the leachate water. This suggests that using soap (1.5 ml and 150 ml) as a leaching agent for Cu extraction from sediment is more effective compared to methanol and Milli-Q water, whether used individually or in combination. Cu concentrations in the leachate water samples were very high and exceeded the guideline values as per the City of Gothenburg for the release of polluted water into water courses, and the classification according to the Swedish EPA for lakes and watercourses. The concentration of Cu in the leachate water indicates the possibility of extracting metals such as Cu from marina sediment.

Leachate water after PEC treatment is indicated by the pink color in Figure 9. In the case of Sample SM3.MQ_S1, which underwent 24 hours of shaking with Milli-Q water as the leaching agent, showed a noticeable reduction in Cu concentration post-PEC treatment (SM3.MQ_S1_PEC). Specifically, Cu decreased from 6 590 µg/L to 6 180 µg/L, representing an approximate 6% reduction but not efficient in reducing risk class. For Sample SM3. 150.Me_S2, which involved a two-step process of leaching with 150 ml methanol and Milli-Q water, it was observed that after PEC treatment (SM3. 150.Me_S2_PEC), the Cu concentration increased from 246 µg/L to 273 µg/L, indicating an increment of approximately 10%. One plausible explanation for this is the potential transfer of Cu back from the electrode. This could be attributed to the sequence of PEC treatments, as SM3. 150.Me_S2_PEC was conducted following SM3.MQ_S1_PEC and the same electrodes were used without washing between each use for all PEC treatments. This suggests that the metal may not have been strongly adhered to the electrode surface, allowing for the observed Cu concentration variation. It should also be considered that there is about a 20% error in the chemical analysis method for metals.

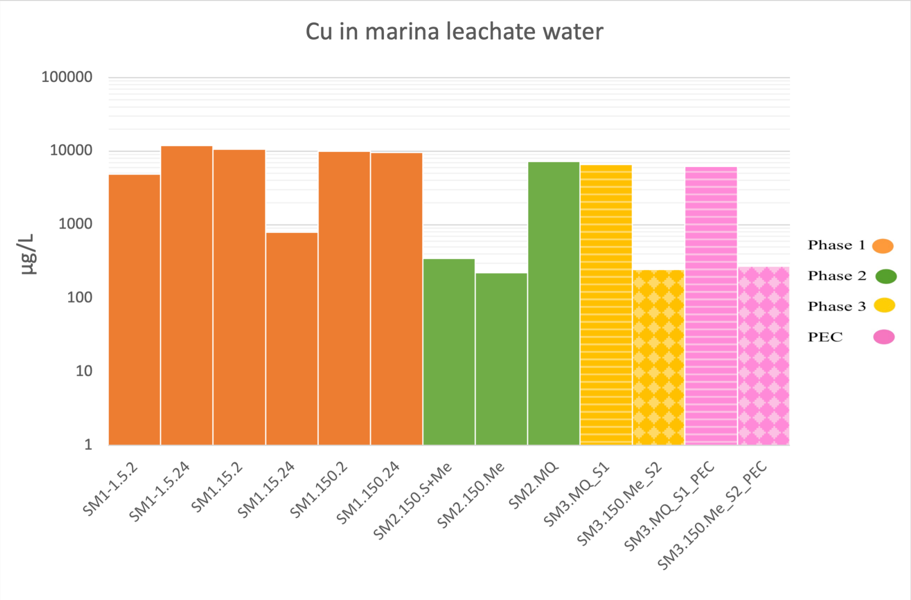

Figure 9: Cu concentration in marina leachate water.
Please note that in the leaching phases, Phase 1 to 3, the aim is to obtain as high concentrations as possible. In contrast, for PEC the goal is to attain as low concentrations as possible.

Figure 10 shows the Zn concentration in the marina leachate water. The highest concentration of Zn was found in Phase 2 with concentrations ranging from 12 400 µg/L to 14 900 µg/L. The concentration in Phase 3 was not as high as anticipated, given that it underwent double leaching. Although the sample SM3. 150.Me_S2 which was the second leaching step in Phase 3 yielded a higher concentration as compared to SM3.MQ_S1, the leachate water from the first step. This indicates the effectiveness of double leaching in extracting metals like Zn but not Cu. Since Zn and Cu are produced from sulfide ores, a possible explanation for this observation can be linked to the structure of the sulfide minerals. Zinc sulfide (ZnS, sphalerite) and copper-bearing minerals ($CuFeS_2$, chalcopyrite) have similar structures. However, chalcopyrite's structure is notably more intricate compared to the relatively simpler structure of sphalerite. Due to this complexity, it requires more powerful leaching conditions to release copper from chalcopyrite, while zinc in sphalerite can be extracted through a relatively more straightforward process (De Oliveira et al., 2012; Schueler et al., 2021).

The leachate water post PEC is indicated with the colour pink in Figure 10. Zn concentration was decreased in both samples. In the case of Sample SM3.MQ_S1, which underwent 24 hours of shaking with Milli-Q water as the leaching agent, a noticeable reduction in Zn concentration was observed post-PEC treatment (SM3.MQ_S1_PEC). Specifically, Zn decreased from 10 100 µg/L to 8 820 µg/L, representing an approximate 13% reduction but not efficient enough to reduce the risk class. For Sample SM3. 150.Me_S2_PEC, which involved a two-step process of leaching with 150 ml methanol and Milli-Q water, it was found that after PEC treatment (SM3. 150.Me_S2_PEC), the Zn concentration was reduced from 34 300 µg/L to 8 680 µg/L, indicating a reduction of approximately 75%. It should be noted that this reduction is not efficient for reducing the environmental risk as per the City of Gothenburg for the release of polluted water into watercourses, and the classification according to the Swedish EPA for lakes and watercourses.

While Cu has lower resistance than Zn meaning faster electron transfer than Zn, it is observed that the reduction of Zn is better using PEC in marina leachate water when compared to Cu. The explanation for this may have been associated with the behavior of metal ions. When copper ions (Cu^{2+}) and zinc ions (Zn^{2+}) interact with certain ligands (molecules that can bind to metal ions), copper ions tend to form more stable coordination compounds than zinc ions. This means that Zn^{2+} does not form coordination compounds as stable as those formed by Cu^{2+} (George et al., 2018). To substantiate this finding, future studies could involve understanding the behavior of metal ions and their complexity when subjected to PEC.

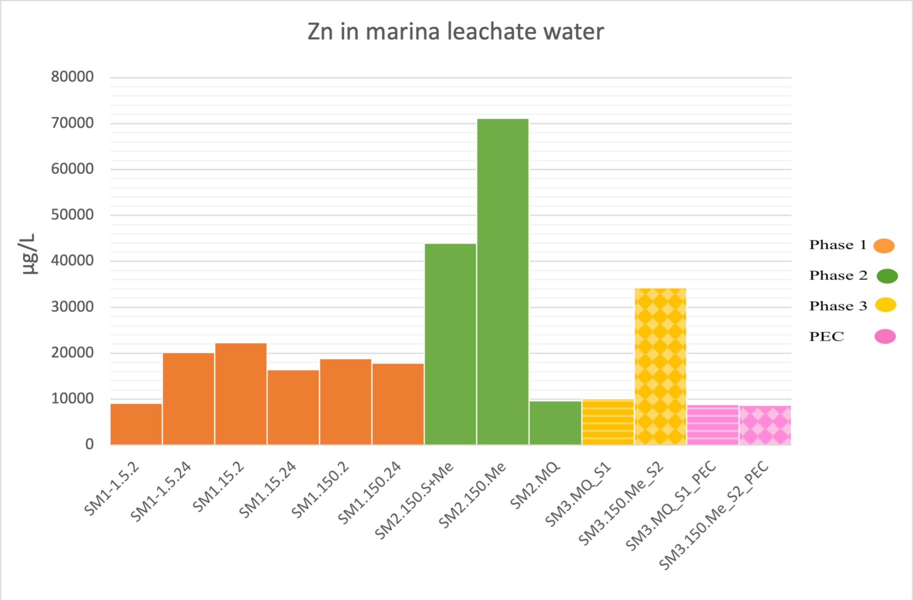

Figure 10: Zn concentration in marina leachate water.
Please note that in the leaching phases, Phase 1 to 3, the aim is to obtain as high concentrations as possible. In contrast, for PEC the goal is to attain as low concentrations as possible.

Figure 11 shows the Cu concentration in traffic runoff sediment leachate water. The highest concentration was observed in Phase 2 with a value of 1 460 µg/L in the sample SG2.MQ which was subjected to 24 hours of shaking with milli-Q water as a leaching agent. The sample SG3.MQ_S1 in Phase 3 has a relatively lower Cu concentration measuring at 589 µg/L. These two samples underwent identical leaching processes, and the variability indicates the need to have duplicate samples to enhance results reliability.

The leachate water, post PEC is indicated by the color pink in Figure 1. Sample SG3.MQ_S, leached with Milli-Q water for 24 hours, showed a notable reduction in Cu concentration after PEC treatment (SG3.MQ_S1_PEC). Specifically, Cu decreased from 589 µg/L to 95 µg/L, representing an approximate 84% reduction, which was not efficient enough to reduce the risk class. In contrast, for Sample SG3. 150.Me_S2, which underwent a two-step leaching process with 150 ml methanol and Milli-Q water, the Cu concentration increased from 250 µg/L to 425 µg/L after PEC treatment (SG3. 150.Me_S2_PEC), indicating an increment of approximately 70%. As previously mentioned, the observed increase in Cu concentration could be due to copper retransferring from the electrode. This may relate to the sequence of PEC treatments, with SG3. 150.Me_S2_PEC following SG3.MQ_S1_PEC, using the same electrodes. This suggests the metal may not have been firmly bonded to the electrode surface, contributing to the Cu concentration variation. It is important to note a potential 20% margin of error in chemical analysis as well.

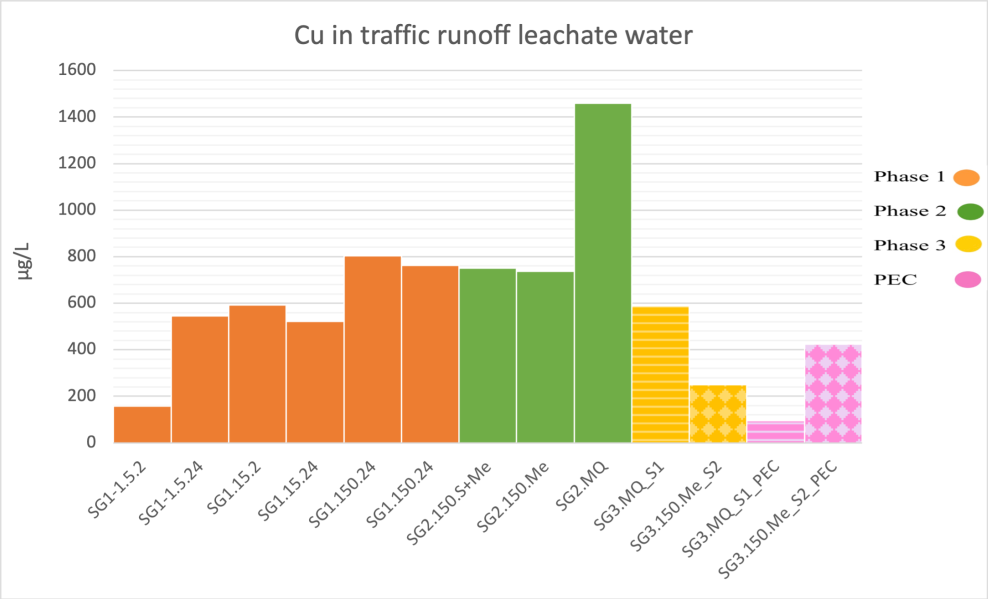

Figure 11: Cu concentration in traffic runoff leachate water

Please note that in the leaching phases, Phase 1 to 3, the aim is to obtain as high concentrations as possible. In contrast, for PEC the goal is to attain as low concentrations as possible.

In Figure 12, the concentration of Zn in traffic runoff leachate water is presented. The highest Zn concentrations were found in Phase 2, ranging from 4 210 µg/L to 42 000 µg/L. Surprisingly, in Phase 3, which involved double leaching (first with Milli-Q water and then with a combination of 150 ml methanol and Milli-Q water), the Zn concentration did not reach the anticipated levels but had a lower concentration than in Phase 2. The second leaching step in Phase 3, SM3. 150.Me_S2, showed a higher Zn concentration compared to SM3.MQ_S1, the leachate from the first step. This highlights the effectiveness of double leaching in extracting Zn but not Cu. As mentioned earlier, the difference in leachability between Zn and Cu can be attributed to their origin from sulfide ores. Zinc sulfide (ZnS, sphalerite) has a simpler structure, making it easier to extract, while copper-bearing minerals like chalcopyrite ($CuFeS_2$) have a more complex structure, requiring harsher leaching conditions for copper extraction (De Oliveira et al., 2012; Schueler et al., 2021).

The leachate water post PEC is indicated with pink in Figure 12. Zn concentration was decreased in the second leaching step by 92%. In the case of Sample SG3.MQ_S1, which underwent 24 hours of shaking with Milli-Q water as the leaching agent, showed a relative increment in Zn concentration post-PEC treatment (SG3.MQ_S1_PEC) with as high as 132% increment. This outcome is unexpected because a fresh electrode was used in the experiment, making the possibility of metal transferring back from the electrode unlikely. Moreover, for the same sample, Cu decreased by 84%, while Zn increased by 132%. While this explanation may be perplexing, this can be linked to the fact that Cu has lower resistance than Zn, which could accelerate the rate of electron transfer (Pinthong et al., 2021). For Sample SG3.150.Me_S2_PEC, which involved a two-step process of leaching with 150 ml methanol and Milli-Q water, it was found that after PEC treatment (SG3.150.Me_S2_PEC), the Zn concentration was reduced with a reduction rate of 92%. Despite this high reduction rate is not efficient to reduce the environmental risk as per the City of Gothenburg for the release of polluted water into water course, and classification according to the Swedish EPA for lakes and watercourses.

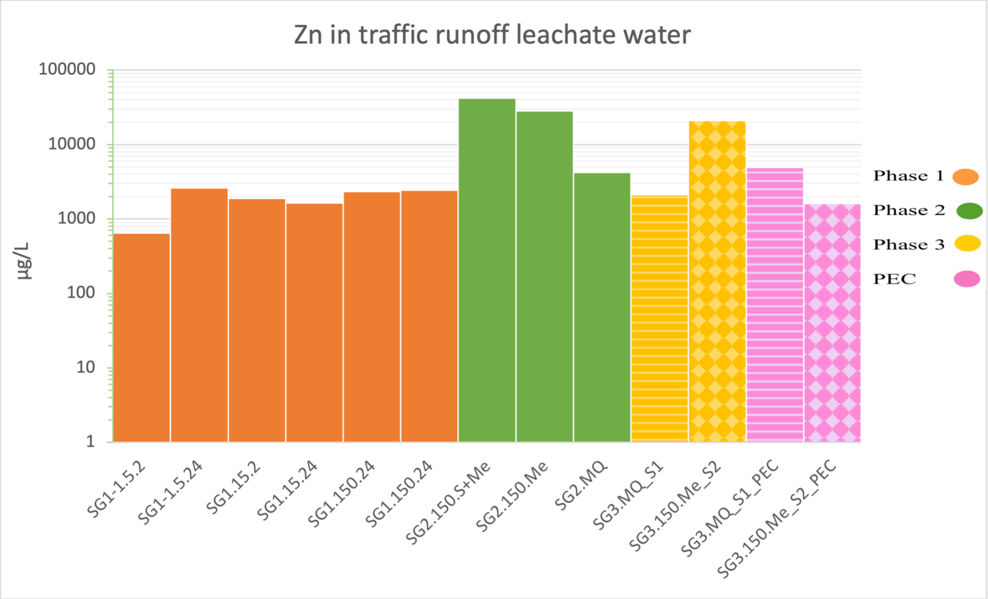

Figure 12: Zn concentration in traffic runoff leachate water
Please note that in the leaching phases, Phase 1 to 3, the aim is to obtain as high concentrations as possible. In contrast, for PEC the goal is to attain as low concentrations as possible.

Determining the optimal leaching agent for extracting metals from sediment into the water phase is difficult due to the varying results observed across different samples in the leachate water. However, the presence of metals specifically Cu and Zn in a marina and traffic runoff sediments leachate water proves, that the leaching process works to a certain extent although it is a small concentration as compared to the concentration in sediment. This observation implies that using a stronger leaching agent could potentially result in a more substantial release of these metals. Additionally, despite the complication of how sediments react to the leaching agents, the presence of metals in the leachate indicates the possibility of extracting metals into a water phase through sediment washing. Furthermore, the PEC treatment indicates potential for reducing Cu and Zn in marina and traffic runoff leachate water, despite fluctuations in their concentrations in certain samples from both sites (Marina and Gårda). While the reduction of Cu and Zn is not substantial, it suggests possible metal recovery. However, it is important to note that the actual quantity of recovered metal remains unknown, as the metals deposited on the electrodes were not measured. Furthermore, the reduction of metals post-PEC was not efficient in reducing the environmental risk as per guideline values. Additionally, Further investigations are required to confirm these findings. To validate these results, future studies could involve using fresh electrodes for each PEC step and exploring the intricate behavior of metal ions when subjected to PEC processes.

5.3.2 Organic Pollutants

The concentration of TBT in marina leachate water is illustrated in Figure 13. The highest concentration of TBT was observed in Phase 1 in samples SM1.150.2 measuring 4 610 µg/L and SM1.150.24 measuring 3 330 µg/L which were subjected to 2 hours and 24 hours of shaking respectively with 150 ml of soap. This indicates that

150 ml soap is a suitable leaching agent to extract TBT into a water phase from contaminated sediment. TBT concentrations in Phase 2 and Phase 3 were comparatively low when compared to Phase 1. This was not anticipated since the primary focus was on enhancing Phase 1 results. Nonetheless, this suggests that using soap (150 ml) as a leaching agent for TBT extraction from sediment is more effective compared to methanol and Milli-Q water, whether used individually or in combination.

The leachate water after PEC treatment is denoted in pink, see Figure 13. It was found that TBT is greatly degraded after treatment with the PEC method. In the case of Sample SM3.MQ_S1, which underwent 24 hours of shaking with Milli-Q water as the leaching agent, showed a noticeable reduction in TBT in SM3.MQ_S1_PEC (post PEC) with a reduction efficiency of as much as 99% (from 6.01 µg/L to 0.051 µg/L). The same was observed in SM3. 150.Me_S2, which involved a two-step process of leaching with 150 methanol and Milli-Q water, yielding a reduction of 99% in SM3. 150.Me_S2_PEC (from 3.14 µg/L to 0.024 µg/L). This highlights the effectiveness of TiO_2 photocatalysis which has the capability to significantly enhance the degradation of organic pollutants. However, it is important to acknowledge that even with this substantial reduction in TBT concentration, it does not meet the water quality guidelines set by the City of Gothenburg for the release of polluted water into water courses, or the Canadian guidelines for marine and freshwater and also the European Union guidelines for surface water. Hence, further treatment is necessary.

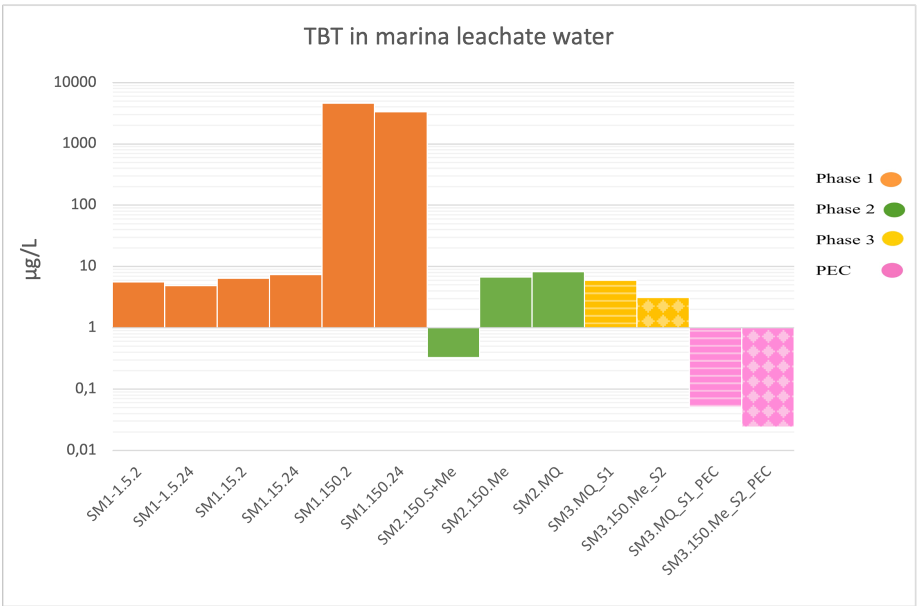

Figure 13: TBT concentration in marina leachate water

Please note that in the leaching phases, Phase 1 to 3, the aim is to obtain as high concentrations as possible. In contrast, for PEC the goal is to attain as low concentrations as possible.

Figure 14 presents the concentration of total PAH-16 in traffic runoff leachate water. The trend observed here is similar to the trend observed in marina leachate water for TBT. The highest concentration of PAH-16 was found in Phase 1 in samples SG1.150.2 measuring 86 µg/L and SG1.150.24 measuring 99 µg/L which were subjected to 2 hours and 24 hours of shaking respectively with 150 ml of soap. This suggests that for extracting PAHs from contaminated sediment into the water phase, using 150 ml of soap as a leaching agent is also effective. PAH-16 concentrations in Phases 1 and 2, though unexpected, indicate that soap (150 ml) is more efficient than methanol and Milli-Q water, whether used separately or in combination for TBT extraction.

For the leachate water post PEC exposure, PAH was degraded significantly in the first sample that is Sample SG3.MQ_S1, which underwent 24 hours of shaking with Milli-Q water as the leaching agent, showed a noticeable reduction in TBT in SG3.MQ_S1_PEC (post-PEC) with a reduction efficiency of as much as 99% (from 6.35 µg/L to 0.071 µg/L). This indicates the efficiency of PEC in degrading PAH using TiO_2 as a photocatalyst. However, this reduction is not efficient enough to meet the water quality criteria set by the City of Gothenburg for the release of polluted water into water courses, or the Canadian guidelines for marine and freshwater, and either not the European Union guidelines for surface water. On the other hand, in SG3. 150.Me_S2, which involved a two-step process of leaching with 150 ml methanol and Milli-Q water, an 300% increment was observed in SG3. 150.Me_S2 _PEC (from 0.465 µg/L to 1.880 µg/L). This phenomenon is quite complex and difficult to explain. One possible reason, though not entirely clear, could be that the electrodes did not fully activate for PAH degradation due to the sequence of PEC treatments with SG3.MQ_S1_PEC followed by SG3. 150.Me_S2_PEC, using the same electrodes. However, this does not account for the notable increase in PAH concentrations after PEC treatment, which should have caused some level of reduction, as seen in other samples. Therefore, it is crucial to consider that a potential 20% margin of error in chemical analysis may have played a role. Therefore, it is essential to consider that a potential 20% margin of error in chemical analysis might have occurred in this case.

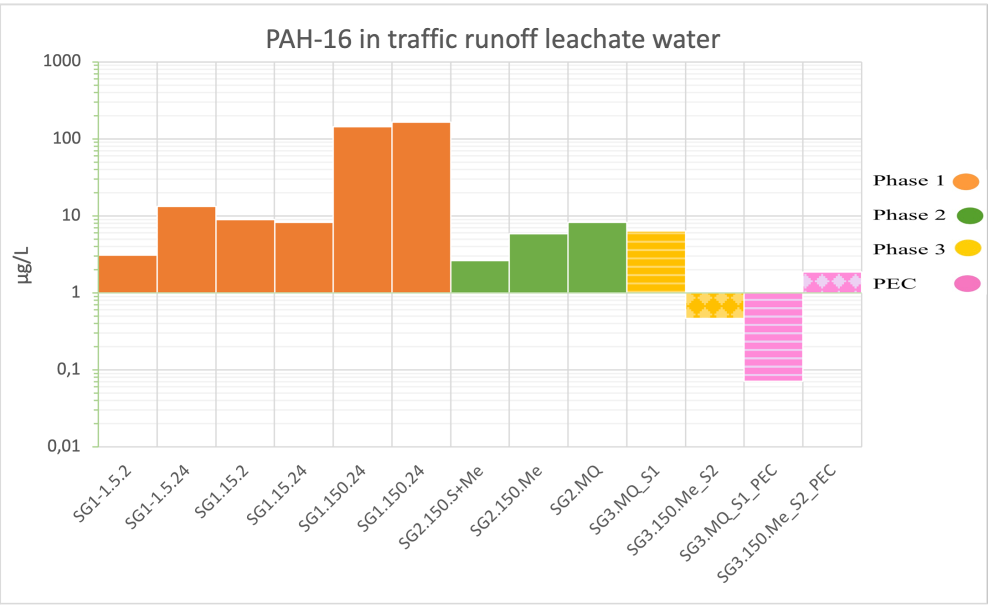

Figure 14: PAH-16 concentration in traffic runoff leachate water

Please note that in the leaching phases, Phase 1 to 3, the aim is to obtain as high concentrations as possible. In contrast, for PEC the goal is to attain as low concentrations as possible.

The optimal leaching agent for the extraction of organic pollutants particularly TBT and PAH is soap (150 ml). This also highlights the challenge of using a single leaching agent to extract both metals and organic pollutants, as indicated by the fluctuating metal results. The results from PEC treatment provide strong indications that organic pollutants specifically TBT and PAH can undergo significant degradation, potentially reaching up to 99%, when exposed to the PEC process. However, it is important to account for possible errors in chemical analysis.

6 Conclusion

In conclusion, this study has revealed several significant findings:

- The leaching method using different concentrations of soap, methanol, and Milli-Q water proves to be suboptimal for the reduction of Cu and Zn in marine sediment. However, it shows some potential, especially in the case of traffic runoff sediment, where the use of 150 ml of soap yielded the best reduction of 28% Cu and 27% Zn using 150 ml soap and 150 ml methanol while keeping the L/S ratio at 10.

- The use of 150 ml of methanol together with Milli-Q shows the best reduction of TBT of 70% and 50% PAH using Milli-Q water alone while keeping the L/S ratio at 10.

- Despite the reduction of these pollutants in the sediments, it is crucial to note that the risk class as defined by guidelines was not lowered.

- Marina and traffic runoff sediments' complexity and distinct characteristics hinder direct comparisons. Factors such as the affinity of the contaminants to the sediment, salt content, organic matter content, and particle size differences contribute to their unique behaviors.

- The presence of metals in both marina and traffic runoff leachate water indicates the potential for extracting metals into the water phase through sediment washing. Although the concentration is relatively low when compared to that in the sediment.

- The study highlights the difficulty in selecting an optimal leaching agent for extracting metals from sediment into the water phase, as results vary across different samples.

- The optimal leaching agent for extracting organic pollutants into water phase, particularly TBT and PAH, is soap (150 ml), achieving the highest concentration of TBT up to 4 610 µg/L and PAH-16 99 µg/L in the leachate. However, challenges arise when attempting to use a single leaching agent for both metals and organic pollutants due to fluctuating metal results.

- PEC treatment has shown positive results in reducing Cu by up to 84% and Zn as high as 92% in traffic runoff sediment leachate water. In the marina sediment leachate water, Zn reduction reached 75%, while Cu reduction was only up to 6%. Further investigations are needed to determine the quantity of recovered metal and its effectiveness in reducing environmental risks.

- The PEC process demonstrates the potential for significant degradation of organic pollutants, particularly TBT and PAH, reaching up to 99%.

- In the light of achieving a significant reduction of pollutants on the leachate by PEC treatment, it remains inefficient to reduce the environmental risks as per guidelines. This further underscores the challenges in achieving satisfactory removal efficiency solely through the tested methods.

This study provides valuable insights into the complexities of sediment washing, metal extraction, organic pollutant degradation, and metal recovery using PEC. The studied leaching process shows strong potential for the reduction of organic pollutants in sediments. However, reductions of metals are low. Furthermore, employing a stronger leaching agent could potentially result in a higher release of pollutants from the sediment into the leachate. The application of PEC indicates a good reduction of metals and organic pollutants in the leachate, emphasizing the efficiency of a stepwise treatment for sediment. The study also highlights the need for further investigations and emphasizes the significance of considering site-specific attributes when executing remediation approaches. Further studies of the whole lifecycle of the developed method using a method like Life cycle Analysis (LCA) from a sustainability perspective will be of interest.

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8 Appendices

Appendix A: Phase 1 metals, OTCs and PAH concentrations

Table A. 1: Phase 1 metals and OTCs concentration of marina sediment samples

Metals [mg/kg]	Original marina sediment samples	SM1.15.24	SM1.150.224
As	10.9	6.31	5.6
Cd	1.096	1.01	0.999
Cr	43.9333	35.7	39.4
Cu	18900	21800	18600
Hg	8.6943	2.51	14.8
Ni	21.8333	19	16.1
Pb	125.3333	132	140
Zn	11800	12600	13900
Organotin [µg /kg]			
MBT	1667	1340	2490
DBT	5733	18400	10700
TBT	57967	71900	74000

Table A. 2: Phase 1 metals and PAH-16 concentration of traffic runoff sediment samples

Metals [mg/kg]	Original traffic runoff sediment sample	SG1.15.24	SG1.150.24
As	1.06	1.31	1.05
Cd	0.162	0.169	0.151
Cr	39	43,6	39,5
Cu	110	120	80
Hg	<0.2	<0.2	<0.2
Ni	26.8	18.9	13.5
Pb	15.8	593	470
Zn	537	3.21	5.33
PAH [µg/kg]			
Naphthalene	66	59	80
Acenaphthylene	24	19	33
Acenaphthene	10	15	19
Fluorene	43	33	37
Phenanthrene	451	282	508
Anthracene	39,3	35,4	70,2
Fluoranthene	556	491	704
Pyrene	1100	908	1240
Benz(a)anthracene	160	136	223

Chrysene	370	248	432
Benz(b)fluoranthene	395	311	529
Benz(k)fluoranthene	106	68	120
Benzo(a)pyrene	300	124	414
Indeno(123cd) pyrene	151	118	201
Dibenz(a,h)anthracene	117	72	137
Benzo(g,h,i)perylene	436	295	580
PAH 16	4310	3210	5330
PAH- L	90	93	132
PAH -M	2190	1750	2560
PAH -H	2040	1370	2640

Table A. 3: Phase 1 metals and OTCs concentration of marina leachate water samples

Metals [µg/L]	**SM1-1.5.2**	**SM1-1.5.24**	**SM1.15.2**	**SM1.15.24**	**SM1.150.2**	**SM1.150.24**
As	12,1	25,1	23,2	9,38	23	25,9
Cd	0,636	1,59	1,39	0,358	1,25	1,4
Cr	45,1	102	90,7	16,5	78	69,9
Cu	4880	11900	10700	786	10000	9660
Hg	0,39	0,93	0,795	0,0506	0,785	0,735
Ni	27,5	63,8	59,5	13,9	46,2	44,6
Pb	89,7	205	172	25,8	178	182
Zn	9140	20200	22300	16400	18800	17900
Organotin [µg/L]						
MBT	0,357	0,507	0,739	1,39	84,9	62,5
DBT	0,795	0,875	1,68	1,71	509	319
TBT	5,62	4,86	6,42	7,45	4610	3330

Table A. 4: Phase 1 metals and PAH-16 concentration of traffic runoff leachate water samples

Metals [µg/L]	**SG1-1.5.2**	**SG1-1.5.24**	**SG1.15.2**	**SG1.15.24**	**SG1.150.2**	**SG1.150.24**
As	1.97	4.34	5.76	3.74	5.73	4.18
Cd	0.203	0.47	0.59	0.41	0.46	0.59
Cr	21.4	79.90	82.10	33.80	93.80	67.80
Cu	157	546	592	522	804	762
Hg	<0.02	0.03	0.07	<0.02	0.11	0.10
Ni	28.9	46.20	46.00	29.90	59.30	45.50
Pb	18.2	77.30	64.90	61.10	88.20	82.60
Zn	644	2 610	1 900	1 640	2 330	2 450
PAH [µg/L]						
Naphthalene	0.071	0.11	0.13	0.09	2.04	<4.44
Acenaphthylene	<0.010	<0.010	<0.020	<0.010	<0.140	<0.150
Acenaphthene	0.031	0.08	<0.110	<0.060	1.02	1.18
Fluorene	0.045	0.14	0.18	0.11	1.98	2.22

Phenanthrene	0.31	1.16	1.45	0.80	18.50	21.70
Anthracene	0.034	0.10	0.08	0.10	2.21	3.37
Fluoranthene	0.453	1.90	1.79	1.19	23.50	28.60
Pyrene	0.758	3.18	<3.48	2.05	39.60	42.60
Benz(a)anthracene	0.137	0.61	0.46	0.35	5.93	6.36
Chrysene	0.278	1.22	1.42	0.93	19.40	21.10
Benz(b)fluoranthene	0.293	1.47	0.98	0.78	9.33	11.10
Benz(k)fluoranthene	<0.080	<0.340	<0.220	<0.180	2.59	3.48
Benzo(a)pyrene	0.152	0.87	0.50	0.43	5.13	5.75
Indeno(123cd) pyrene						
Dibenz(a,h)anthracene	0.062	0.25	0.22	0.18	1.87	2.43
Benzo(g,h,i)perylene	0.353	1.56	1.28	0.96	9.89	12.00
	0.125	0.62	0.47	0.34	2.30	2.97
PAH 16	3.1	13.30	8.95	8.30	145.00	165.00
PAH -L	0.102	0.19	0.13	0.09	3.06	1.18
PAH -M	1.6	6.48	3.50	4.24	85.80	98.50
PAH -H	1.4	6.60	5.31	3.96	56.40	65.20

Appendix B: Phase 2 metals, OTCs and PAH concentrations

Table B. 1: Phase 2 metals and OTCs concentration of marina sediment samples

Metals [mg/kg]	Original marina sediment samples	SM2. 150.S+Me	SM2. 150.Me	SM2.MQ
As	10.9	8.6	8.17	6.07
Cd	1.096	5.76	0.97	0.778
Cr	43.9333	36.1	30	26.4
Cu	18900	19200	20500	18300
Hg	8.6943	19.1	1.11	0.558
Ni	21.8333	17.4	16.6	17.4
Pb	125.3333	105	169	897
Zn	11800	12400	14900	13800
Organotin [mg/kg]				
MBT	1.6667	1.12	1.17	1.84
DBT	5.7333	6.7	2.83	7.55
TBT	57.9667	61.6	17.4	53.6

Table B. 2: Phase 2 metals and OTCs concentration of marina leachate water samples

Metals [µg/L]	**SM2. 150.S+Me**	**SM2. 150.Me**	**SM2.MQ**
As	40.8	30	13
Cd	0.0986	0.0805	0.735
Cr	6.94	2.58	49.6
Cu	350	223	7220
Hg	0.0205	<0.02	0.51
Ni	79	129	36.2
Pb	4.82	4.5	102
Zn	44000	71100	9670
Organotin [µg/L]			
MBT	0.0208	0.0191	0.325
DBT	0.134	0.24	2.63
TBT	0.327	6.73	8.26

Table B. 3: Phase 2 metals and PAH-16 concentration of traffic runoff sediment samples

Metals [mg/kg]	**Original Traffic runoff sediment sample**	**SG2. 150.S+Me**	**SG2. 150.Me**	**SG2.MQ**
As	1.06	1.31	1.29	1.35
Cd	0.162	0.137	0.164	0.17
Cr	39	37.3	42.3	34.6

Cu	110	95.1	112	98.2
Hg	<0.2	<0.2	<0.2	<0.2
Ni	26.8	20.8	25.1	28.2
Pb	15.8	16.7	19.4	16.4
Zn	537	388	430	526
PAH [mg/kg]				
Naphthalene	0.066	0.08	0.021	0.072
Acenaphthylene	0.024	0.03	0.01	<0.010
Acenaphthene	<0.010	0.015	0.014	0.02
Fluorene	0.043	0.045	0.032	0.036
Phenanthrene	0.451	0.475	0.271	0.238
Anthracene	0.0393	0.0588	0.0341	0.0265
Fluoranthene	0.556	0.757	0.406	0.322
Pyrene	1.1	1.26	0.628	0.423
Benz(a)anthracene	0.16	0.206	0.109	0.088
Chrysene	0.37	0.545	0.253	0.16
Benz(b)fluoranthene	0.395	0.466	0.251	0.141
Benz(k)fluoranthene	0.106	0.119	0.065	0.039
Benzo(a)pyrene	0.3	0.354	0.147	0.108
Dibenz(a.h)anthracene	0.117	0.101	0.049	0.048
Benzo(g.h.i)perylene	0.436	0.484	0.238	0.173
Indeno(123cd) pyrene	0.151	0.224	0.08	0.065
PAH 16	4.31	5.22	2.61	1.96
PAH -L	0.09	0.125	0.045	0.092
PAH -M	2.19	2.6	1.37	1.04
PAH -H	2.04	2.5	1.19	0.822

Table B. 4: Phase 2 metals and PAH-16 concentration of traffic runoff leachate water samples

Metals [µg/L]	**SG2. 150.S+Me**	**SG2. 150.Me**	**SG2.MQ**
As	18.6	10.2	6.59
Cd	3.16	3.99	1.12
Cr	176	114	155
Cu	751	737	1460
Hg	0.11	0.0801	0.0954
Ni	519	520	92.1
Pb	71.3	61.6	139
Zn	42000	28400	4210
PAH [µg/L]			
Naphthalene	<0.120	0.139	0.13
Acenaphthylene	<0.010	<0.010	<0.020
Acenaphthene	<0.040	<0.060	<0.050
Fluorene	<0.130	<0.120	<0.120
Phenanthrene	0.861	0.771	0.968
Anthracene	0.084	0.094	0.112

Fluoranthene	1.1	1.13	1.6
Pyrene	<1.71	1.89	2.68
Benz(a)anthracene	<0.290	0.36	0.516
Chrysene	<0.860	0.601	0.882
Benz(b)fluoranthene	<0.610	<0.790	<1.32
Benz(k)fluoranthene	<0.140	<0.130	<0.280
Benzo(a)pyrene	<0.240	<0.430	<0.600
Dibenz(a,h)anthracene	<0.110	<0.200	<0.280
Benzo(g,h,i)perylene	0.592	0.915	1.4
Indeno(123cd) pyrene	<0.230	<0.350	<0.610
PAH 16	2.64	5.9	8.29
PAH -L	0.085	0.139	0.13
PAH -M	2.04	3.88	5.36
PAH -H	0.592	1.88	2.8

Appendix C: Phase 3 metals, OTCs and PAH concentrations

Table C. 1: Phase 3 metals and OTCs concentration of marina sediment samples

Metals [mg/kg]	Original marina sediment samples	SM3. 150.Me_S2
As	10.9	8.08
Cd	1.096	0.924
Cr	43.9333	42.3
Cu	18900	23300
Hg	8.6943	10.3
Ni	21.8333	22.4
Pb	125.3333	158
Zn	11800	15800
Organotin [mg/kg]		
MBT	1.6667	0.923
DBT	5.7333	1.41
TBT	57.9667	36.1

Table C. 2: Phase 3 metals and OTCs concentration of marina leachate water samples

Metals [µg/L]	SM3.MQ_S1	SM3. 150.Me_S2
As	13	27.5
Cd	0.773	<0.1
Cr	42.8	1.83
Cu	6590	246
Hg	<1	<1
Ni	31.3	66.3
Pb	113	4.27
Zn	10100	34300
Organotin [µg/L]		
MBT	0.365	0.0106
DBT	2.31	0.0961
TBT	6.01	3.14

Table C. 3: Phase 3 metals and PAH-16 concentration of marina sediment samples

Metals [mg/kg]	Original Traffic runoff sediment sample	SG3. 150.Me_S2
As	1.06	1.11
Cd	0.162	0.165
Cr	39	41.3
Cu	110	107
Hg	<0.2	<0.2
Ni	26.8	24

Pb	15.8	17.7
Zn	537	385
PAH [mg/kg]		
Naphthalene	0.066	0.058
Acenaphthylene	0.024	0.036
Acenaphthene	<0.010	0.02
Fluorene	0.043	0.062
Phenanthrene	0.451	0.725
Anthracene	0.0393	0.135
Fluoranthene	0.556	0.954
Pyrene	1.1	1.37
Benz(a)anthracene	0.16	0.315
Chrysene	0.37	0.449
Benz(b)fluoranthene	0.395	0.566
Benz(k)fluoranthene	0.106	0.193
Benzo(a)pyrene	0.3	0.429
Dibenz(a,h)anthracene	0.117	0.173
Benzo(g,h,i)perylene	0.436	0.578
Indeno(123cd) pyrene	0.151	0.217
PAH 16	4.31	6.28
PAH -L	0.09	0,114
PAH -M	2.19	3.25
PAH -H	2.04	2.92

Table C. 4: Phase 3 metals and PAH-16 concentration of traffic runoff leachate water samples

Metals [µg/L]	**SG3.MQ_S1**	**SG3. 150.Me_S2**
As	4.25	3.38
Cd	0.437	3.46
Cr	73.2	33
Cu	589	250
Hg	<1	<1
Ni	58	316
Pb	71.1	29
Zn	2130	21000
PAH [µg/L]		
Naphthalene	0.083	0.074
Acenaphthylene	<0.010	<0.010
Acenaphthene	0.087	<0.020
Fluorene	0.067	0.022
Phenanthrene	0.562	0.088
Anthracene	<0.110	<0.010
Fluoranthene	0.913	0.061
Pyrene	1.41	0.094

Benz(a)anthracene	0.319	0.015
Chrysene	0.582	0.032
Benz(b)fluoranthene	0.773	0.024
Benz(k)fluoranthene	0.152	<0.010
Benzo(a)pyrene	0.452	0.0147
Dibenz(a,h)anthracene	<0.130	<0.010
Benzo(g,h,i)perylene	0.654	0.027
Indeno(123cd) pyrene	0.294	0.013
PAH 16	6.35	0.465
PAH -L	0.17	0.074
PAH -M	2.95	0.265
PAH -H	3.23	0.126

Appendix D: Metals, OTCs and PAH concentrations after PEC

Table D. 1: Metals and OTCs concentration of marina leachate water samples after PEC treatment

Metals [µg/L]	SM3.MQ_S1_PEC	SM3. 150.Me_S2_PEC
As	14.2	19.5
Cd	0.391	0.479
Cr	55.1	2.88
Cu	6180	273
Hg	0.597	0.05
Ni	38.3	26.9
Pb	117	13.1
Zn	8820	8680
Organotin [µg/L]		
MBT	0.00512	0.0857
DBT	0.0995	0.0523
TBT	0.051	0.0242

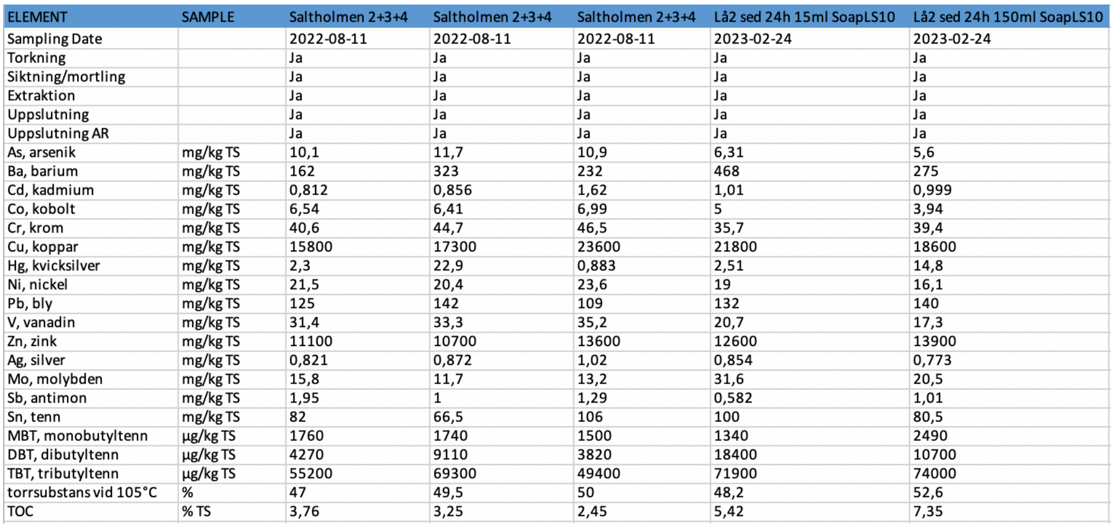
Table D. 2: Metals and PAH-16 concentration of traffic runoff leachate water samples after PEC treatment

Metals [µg/L]	SG3. MQ_S1_PEC	SG3. 150.Me_S2_PEC
As	3.27	4.09
Cd	0.525	0.506
Cr	46.6	61.5
Cu	94.8	0.425
Hg	0.0578	0.144
Ni	157	0.0494
Pb	24.4	48.5
Zn	4950	1630
PAH [µg/L]		
Naphthalene	<0.0010	<0.020
Acenaphthylene	<0.0010	0.023
Acenaphthene	<0.0010	0.0027
Fluorene	0.00062	0.0069
Phenanthrene	0.0046	0.09
Anthracene	0.0012	0.05
Fluoranthene	0.013	0.35
Pyrene	0.011	0.28
Benz(a)anthracene	0.0055	0.099
Chrysene	0.0068	0.19
Benz(b)fluoranthene	0.0069	0.24

Benz(k)fluoranthene	0.0026	0.086
Benzo(a)pyrene	0.004	0.11
Dibenz(a,h)anthracene	0.0026	0.048
Benzo(g,h,i)perylene	0.0067	0.19
Indeno(123cd) pyrene	0.0055	0.11
PAH 16	0.071	1.88
PAH -L	0.0015	0.0257
PAH -M	0.0304	0.777
PAH -H	0.0406	1.07

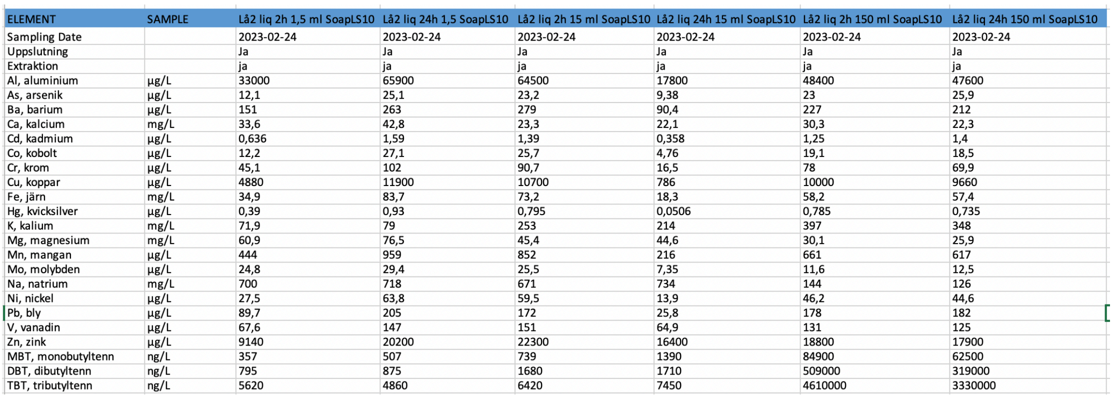
Appendix E: Phase 1 original results from ALS Scandinavian AB

Table E. 1: Marina original sediment and sediment after leaching phase 1.



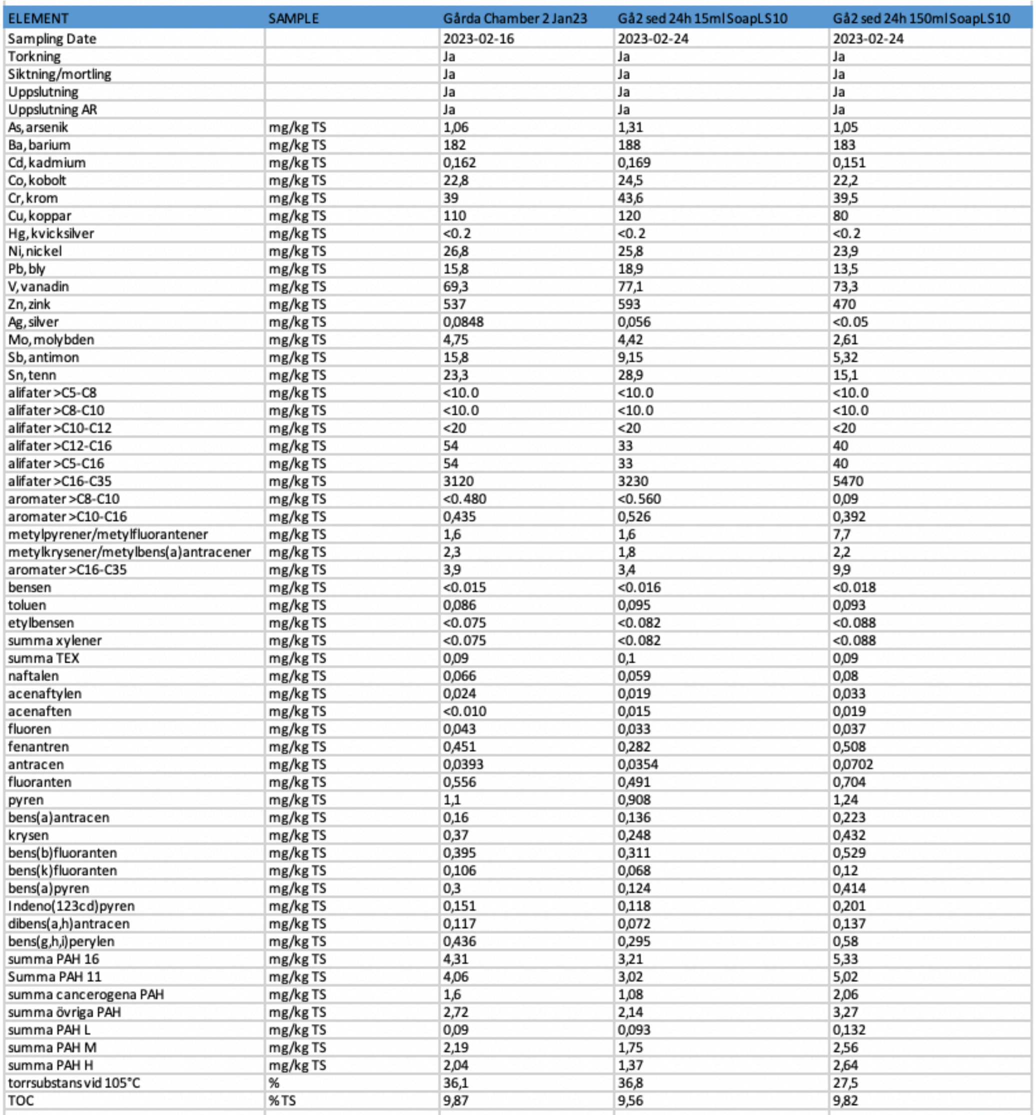
ELEMENT	SAMPLE	Saltholmen 2+3+4	Saltholmen 2+3+4	Saltholmen 2+3+4	Lå2 sed 24h 15ml SoapLS10	Lå2 sed 24h 150ml SoapLS10
Sampling Date		2022-08-11	2022-08-11	2022-08-11	2023-02-24	2023-02-24
Torkning		Ja	Ja	Ja	Ja	Ja
Siktning/mortling		Ja	Ja	Ja	Ja	Ja
Extraktion		Ja	Ja	Ja	Ja	Ja
Uppslutning		Ja	Ja	Ja	Ja	Ja
Uppslutning AR		Ja	Ja	Ja	Ja	Ja
As, arsenik	mg/kg TS	10,1	11,7	10,9	6,31	5,6
Ba, barium	mg/kg TS	162	323	232	468	275
Cd, kadmium	mg/kg TS	0,812	0,856	1,62	1,01	0,999
Co, kobolt	mg/kg TS	6,54	6,41	6,99	5	3,94
Cr, krom	mg/kg TS	40,6	44,7	46,5	35,7	39,4
Cu, koppar	mg/kg TS	15800	17300	23600	21800	18600
Hg, kvicksilver	mg/kg TS	2,3	22,9	0,883	2,51	14,8
Ni, nickel	mg/kg TS	21,5	20,4	23,6	19	16,1
Pb, bly	mg/kg TS	125	142	109	132	140
V, vanadin	mg/kg TS	31,4	33,3	35,2	20,7	17,3
Zn, zink	mg/kg TS	11100	10700	13600	12600	13900
Ag, silver	mg/kg TS	0,821	0,872	1,02	0,854	0,773
Mo, molybden	mg/kg TS	15,8	11,7	13,2	31,6	20,5
Sb, antimon	mg/kg TS	1,95	1	1,29	0,582	1,01
Sn, tenn	mg/kg TS	82	66,5	106	100	80,5
MBT, monobutyltenn	µg/kg TS	1760	1740	1500	1340	2490
DBT, dibutyltenn	µg/kg TS	4270	9110	3820	18400	10700
TBT, tributyltenn	µg/kg TS	55200	69300	49400	71900	74000
torrsubstans vid 105°C	%	47	49,5	50	48,2	52,6
TOC	% TS	3,76	3,25	2,45	5,42	7,35

Table E. 2: Marina leachate water after leaching phase 1.



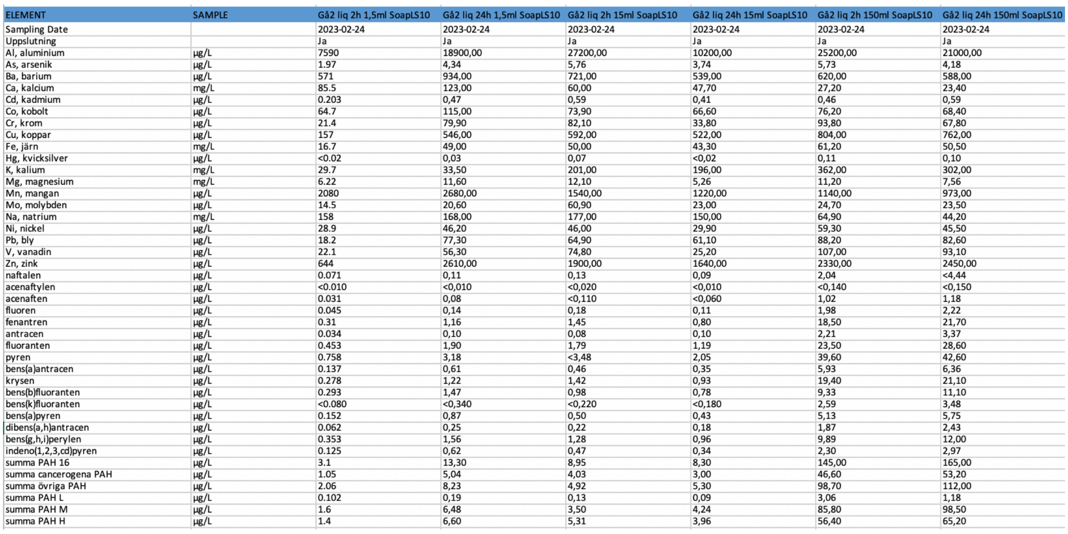
ELEMENT	SAMPLE	Lå2 liq 2h 1,5 ml SoapLS10	Lå2 liq 24h 1,5 SoapLS10	Lå2 liq 2h 15 ml SoapLS10	Lå2 liq 24h 15 ml SoapLS10	Lå2 liq 2h 150 ml SoapLS10	Lå2 liq 24h 150 ml SoapLS10
Sampling Date		2023-02-24	2023-02-24	2023-02-24	2023-02-24	2023-02-24	2023-02-24
Uppslutning		Ja	Ja	Ja	Ja	Ja	Ja
Extraktion		ja	ja	ja	ja	ja	ja
Al, aluminium	µg/L	33000	65900	64500	17800	48400	47600
As, arsenik	µg/L	12,1	25,1	23,2	9,38	23	25,9
Ba, barium	µg/L	151	263	279	90,4	227	212
Ca, kalcium	mg/L	33,6	42,8	23,3	22,1	30,3	22,3
Cd, kadmium	µg/L	0,636	1,59	1,39	0,358	1,25	1,4
Co, kobolt	µg/L	12,2	27,1	25,7	4,76	19,1	18,5
Cr, krom	µg/L	45,1	102	90,7	16,5	78	69,9
Cu, koppar	µg/L	4880	11900	10700	786	10000	9660
Fe, järn	mg/L	34,9	83,7	73,2	18,3	58,2	57,4
Hg, kvicksilver	µg/L	0,39	0,93	0,795	0,0506	0,785	0,735
K, kalium	mg/L	71,9	79	253	214	397	348
Mg, magnesium	mg/L	60,9	76,5	45,4	44,6	30,1	25,9
Mn, mangan	µg/L	444	959	852	216	661	617
Mo, molybden	µg/L	24,8	29,4	25,5	7,35	11,6	12,5
Na, natrium	mg/L	700	718	671	734	144	126
Ni, nickel	µg/L	27,5	63,8	59,5	13,9	46,2	44,6
Pb, bly	µg/L	89,7	205	172	25,8	178	182
V, vanadin	µg/L	67,6	147	151	64,9	131	125
Zn, zink	µg/L	9140	20200	22300	16400	18800	17900
MBT, monobutyltenn	ng/L	357	507	739	1390	84900	62500
DBT, dibutyltenn	ng/L	795	875	1680	1710	509000	319000
TBT, tributyltenn	ng/L	5620	4860	6420	7450	4610000	3330000

Table E. 3: Traffic runoff original sediment and sediment after leaching phase 1.



ELEMENT	SAMPLE	Gårda Chamber 2 Jan23	Gå2 sed 24h 15ml SoapLS10	Gå2 sed 24h 150ml SoapLS10
Sampling Date		2023-02-16	2023-02-24	2023-02-24
Torkning		Ja	Ja	Ja
Siktning/mortling		Ja	Ja	Ja
Uppslutning		Ja	Ja	Ja
Uppslutning AR		Ja	Ja	Ja
As, arsenik	mg/kg TS	1,06	1,31	1,05
Ba, barium	mg/kg TS	182	188	183
Cd, kadmium	mg/kg TS	0,162	0,169	0,151
Co, kobolt	mg/kg TS	22,8	24,5	22,2
Cr, krom	mg/kg TS	39	43,6	39,5
Cu, koppar	mg/kg TS	110	120	80
Hg, kvicksilver	mg/kg TS	<0.2	<0.2	<0.2
Ni, nickel	mg/kg TS	26,8	25,8	23,9
Pb, bly	mg/kg TS	15,8	18,9	13,5
V, vanadin	mg/kg TS	69,3	77,1	73,3
Zn, zink	mg/kg TS	537	593	470
Ag, silver	mg/kg TS	0,0848	0,056	<0.05
Mo, molybden	mg/kg TS	4,75	4,42	2,61
Sb, antimon	mg/kg TS	15,8	9,15	5,32
Sn, tenn	mg/kg TS	23,3	28,9	15,1
alifater >C5-C8	mg/kg TS	<10.0	<10.0	<10.0
alifater >C8-C10	mg/kg TS	<10.0	<10.0	<10.0
alifater >C10-C12	mg/kg TS	<20	<20	<20
alifater >C12-C16	mg/kg TS	54	33	40
alifater >C5-C16	mg/kg TS	54	33	40
alifater >C16-C35	mg/kg TS	3120	3230	5470
aromater >C8-C10	mg/kg TS	<0.480	<0.560	0,09
aromater >C10-C16	mg/kg TS	0,435	0,526	0,392
metylpyrener/metylfluorantener	mg/kg TS	1,6	1,6	7,7
metylkrysener/metylbens(a)antracener	mg/kg TS	2,3	1,8	2,2
aromater >C16-C35	mg/kg TS	3,9	3,4	9,9
bensen	mg/kg TS	<0.015	<0.016	<0.018
toluen	mg/kg TS	0,086	0,095	0,093
etylbensen	mg/kg TS	<0.075	<0.082	<0.088
summa xylener	mg/kg TS	<0.075	<0.082	<0.088
summa TEX	mg/kg TS	0,09	0,1	0,09
naftalen	mg/kg TS	0,066	0,059	0,08
acenaftylen	mg/kg TS	0,024	0,019	0,033
acenaften	mg/kg TS	<0.010	0,015	0,019
fluoren	mg/kg TS	0,043	0,033	0,037
fenantren	mg/kg TS	0,451	0,282	0,508
antracen	mg/kg TS	0,0393	0,0354	0,0702
fluoranten	mg/kg TS	0,556	0,491	0,704
pyren	mg/kg TS	1,1	0,908	1,24
bens(a)antracen	mg/kg TS	0,16	0,136	0,223
krysen	mg/kg TS	0,37	0,248	0,432
bens(b)fluoranten	mg/kg TS	0,395	0,311	0,529
bens(k)fluoranten	mg/kg TS	0,106	0,068	0,12
bens(a)pyren	mg/kg TS	0,3	0,124	0,414
Indeno(123cd)pyren	mg/kg TS	0,151	0,118	0,201
dibens(a,h)antracen	mg/kg TS	0,117	0,072	0,137
bens(g,h,i)perylen	mg/kg TS	0,436	0,295	0,58
summa PAH 16	mg/kg TS	4,31	3,21	5,33
Summa PAH 11	mg/kg TS	4,06	3,02	5,02
summa cancerogena PAH	mg/kg TS	1,6	1,08	2,06
summa övriga PAH	mg/kg TS	2,72	2,14	3,27
summa PAH L	mg/kg TS	0,09	0,093	0,132
summa PAH M	mg/kg TS	2,19	1,75	2,56
summa PAH H	mg/kg TS	2,04	1,37	2,64
torrsubstans vid 105°C	%	36,1	36,8	27,5
TOC	% TS	9,87	9,56	9,82

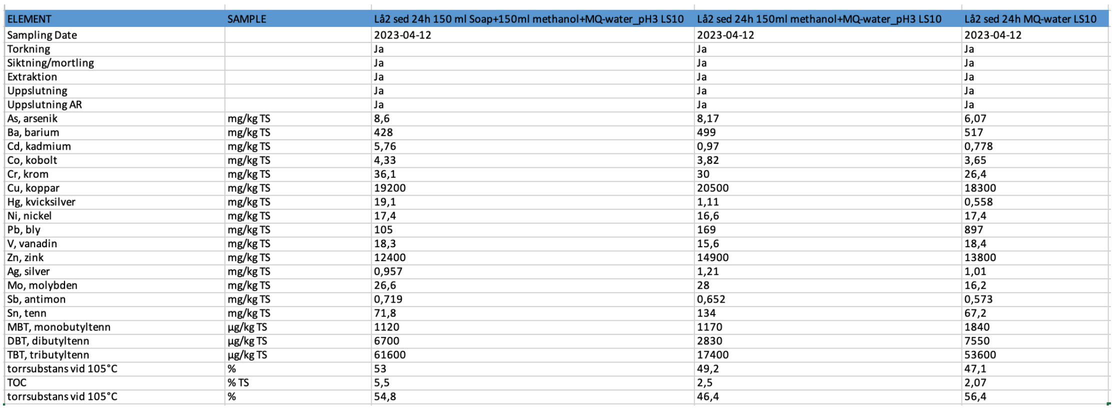
Table E. 4: Traffic runoff leachate water after leaching phase 1.



ELEMENT	SAMPLE	Gå2 liq 2h 1,5ml SoapLS10	Gå2 liq 24h 1,5ml SoapLS10	Gå2 liq 2h 15ml SoapLS10	Gå2 liq 24h 15ml SoapLS10	Gå2 liq 2h 150ml SoapLS10	Gå2 liq 24h 150ml SoapLS10
Sampling Date		2023-02-24	2023-02-24	2023-02-24	2023-02-24	2023-02-24	2023-02-24
Uppslutning		Ja	Ja	Ja	Ja	Ja	Ja
Al, aluminium	µg/L	7590	18900,00	27200,00	10200,00	25200,00	21000,00
As, arsenik	µg/L	1.97	4,34	5,76	3,74	5,73	4,18
Ba, barium	µg/L	571	934,00	721,00	539,00	620,00	588,00
Ca, kalcium	mg/L	85.5	123,00	60,00	47,70	27,20	23,40
Cd, kadmium	µg/L	0.203	0,47	0,59	0,41	0,46	0,59
Co, kobolt	µg/L	64.7	115,00	73,90	66,60	76,20	68,40
Cr, krom	µg/L	21.4	79,90	82,10	33,80	93,80	67,80
Cu, koppar	µg/L	157	546,00	592,00	522,00	804,00	762,00
Fe, järn	mg/L	16.7	49,00	50,00	43,30	61,20	50,50
Hg, kvicksilver	µg/L	<0.02	0,03	0,07	<0,02	0,11	0,10
K, kalium	mg/L	29.7	33,50	201,00	196,00	362,00	302,00
Mg, magnesium	mg/L	6.22	11,60	12,10	5,26	11,20	7,56
Mn, mangan	µg/L	2080	2680,00	1540,00	1220,00	1140,00	973,00
Mo, molybden	µg/L	14.5	20,60	60,90	23,00	24,70	23,50
Na, natrium	mg/L	158	168,00	177,00	150,00	64,90	44,20
Ni, nickel	µg/L	28.9	46,20	46,00	29,90	59,30	45,50
Pb, bly	µg/L	18.2	77,30	64,90	61,10	88,20	82,60
V, vanadin	µg/L	22.1	56,30	74,80	25,20	107,00	93,10
Zn, zink	µg/L	644	2610,00	1900,00	1640,00	2330,00	2450,00
naftalen	µg/L	0.071	0,11	0,13	0,09	2,04	<4,44
acenaftylen	µg/L	<0.010	<0,010	<0,020	<0,010	<0,140	<0,150
acenaften	µg/L	0.031	0,08	<0,110	<0,060	1,02	1,18
fluoren	µg/L	0.045	0,14	0,18	0,11	1,98	2,22
fenantren	µg/L	0.31	1,16	1,45	0,80	18,50	21,70
antracen	µg/L	0.034	0,10	0,08	0,10	2,21	3,37
fluoranten	µg/L	0.453	1,90	1,79	1,19	23,50	28,60
pyren	µg/L	0.758	3,18	<3,48	2,05	39,60	42,60
bens(a)antracen	µg/L	0.137	0,61	0,46	0,35	5,93	6,36
krysen	µg/L	0.278	1,22	1,42	0,93	19,40	21,10
bens(b)fluoranten	µg/L	0.293	1,47	0,98	0,78	9,33	11,10
bens(k)fluoranten	µg/L	<0.080	<0,340	<0,220	<0,180	2,59	3,48
bens(a)pyren	µg/L	0.152	0,87	0,50	0,43	5,13	5,75
dibens(a,h)antracen	µg/L	0.062	0,25	0,22	0,18	1,87	2,43
bens(g,h,i)perylen	µg/L	0.353	1,56	1,28	0,96	9,89	12,00
indeno(1,2,3,cd)pyren	µg/L	0.125	0,62	0,47	0,34	2,30	2,97
summa PAH 16	µg/L	3.1	13,30	8,95	8,30	145,00	165,00
summa cancerogena PAH	µg/L	1.05	5,04	4,03	3,00	46,60	53,20
summa övriga PAH	µg/L	2.06	8,23	4,92	5,30	98,70	112,00
summa PAH L	µg/L	0.102	0,19	0,13	0,09	3,06	1,18
summa PAH M	µg/L	1.6	6,48	3,50	4,24	85,80	98,50
summa PAH H	µg/L	1.4	6,60	5,31	3,96	56,40	65,20

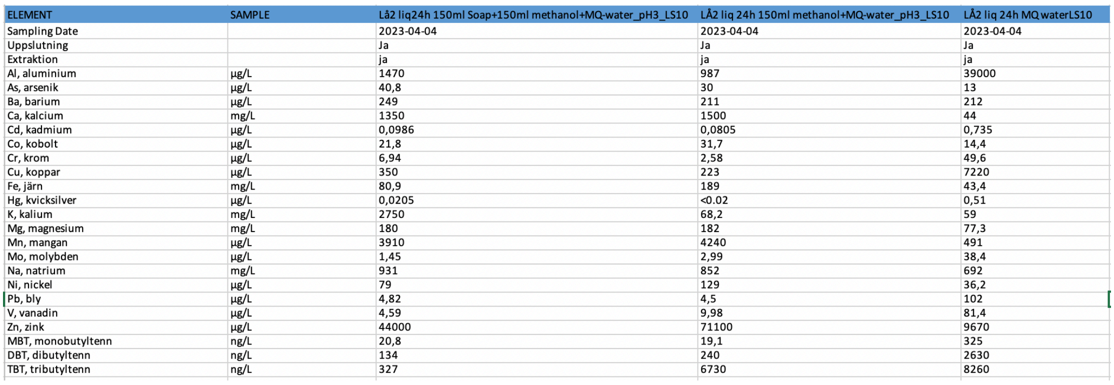
Appendix F: Phase 2 original results from ALS Scandinavian AB

Table F. 1: Marina sediment after leaching phase 2.



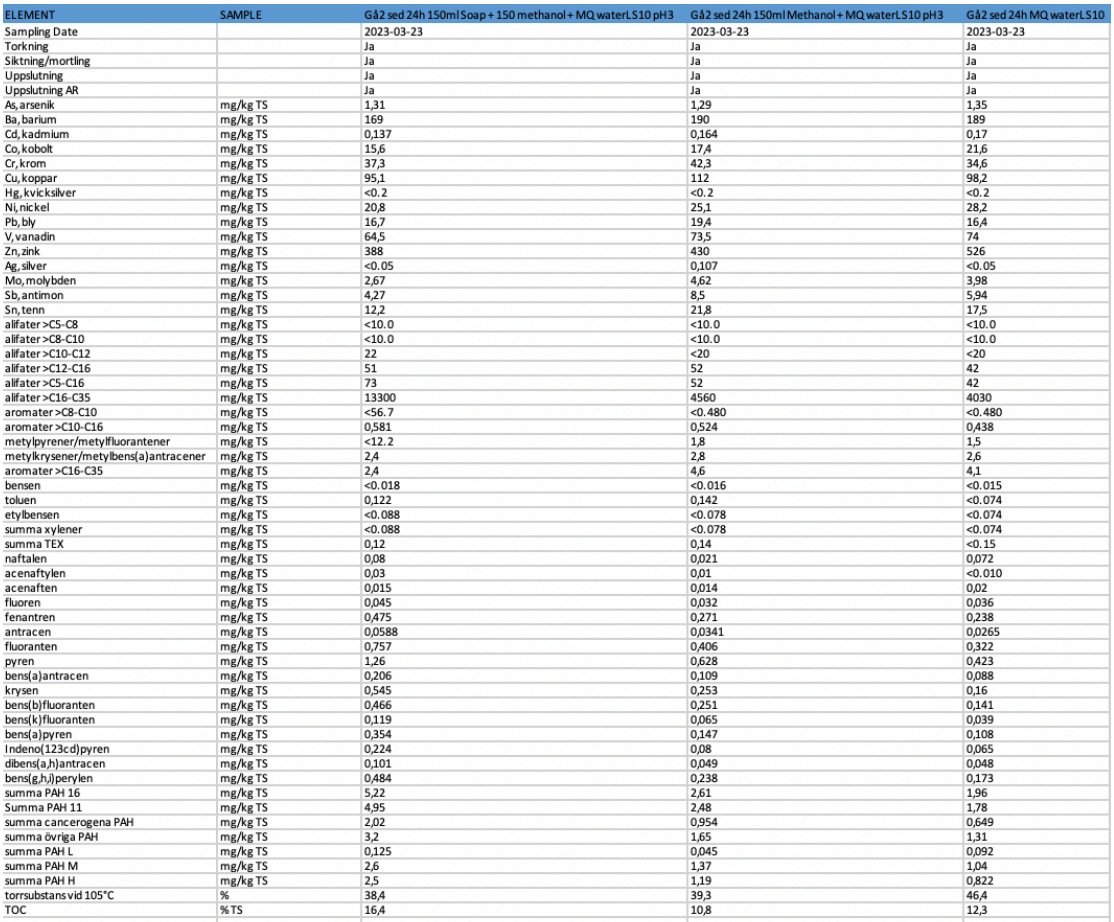
ELEMENT	SAMPLE	Lå2 sed 24h 150 ml Soap+150ml methanol+MQ-water_pH3 LS10	Lå2 sed 24h 150ml methanol+MQ-water_pH3 LS10	Lå2 sed 24h MQ-water LS10
Sampling Date		2023-04-12	2023-04-12	2023-04-12
Torkning		Ja	Ja	Ja
Siktning/mortling		Ja	Ja	Ja
Extraktion		Ja	Ja	Ja
Uppslutning		Ja	Ja	Ja
Uppslutning AR		Ja	Ja	Ja
As, arsenik	mg/kg TS	8,6	8,17	6,07
Ba, barium	mg/kg TS	428	499	517
Cd, kadmium	mg/kg TS	5,76	0,97	0,778
Co, kobolt	mg/kg TS	4,33	3,82	3,65
Cr, krom	mg/kg TS	36,1	30	26,4
Cu, koppar	mg/kg TS	19200	20500	18300
Hg, kvicksilver	mg/kg TS	19,1	1,11	0,558
Ni, nickel	mg/kg TS	17,4	16,6	17,4
Pb, bly	mg/kg TS	105	169	897
V, vanadin	mg/kg TS	18,3	15,6	18,4
Zn, zink	mg/kg TS	12400	14900	13800
Ag, silver	mg/kg TS	0,957	1,21	1,01
Mo, molybden	mg/kg TS	26,6	28	16,2
Sb, antimon	mg/kg TS	0,719	0,652	0,573
Sn, tenn	mg/kg TS	71,8	134	67,2
MBT, monobutyltenn	µg/kg TS	1120	1170	1840
DBT, dibutyltenn	µg/kg TS	6700	2830	7550
TBT, tributyltenn	µg/kg TS	61600	17400	53600
torrsubstans vid 105°C	%	53	49,2	47,1
TOC	% TS	5,5	2,5	2,07
torrsubstans vid 105°C	%	54,8	46,4	56,4

Table F. 2: Marina leachate water after leaching phase 2.



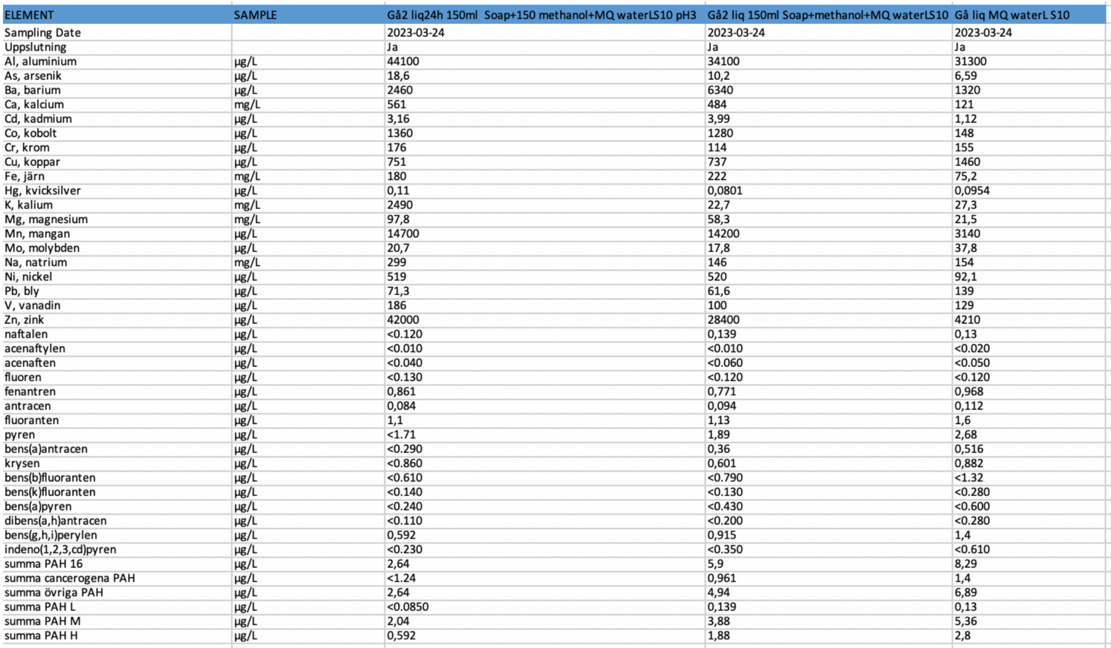
ELEMENT	SAMPLE	Lå2 liq24h 150ml Soap+150ml methanol+MQ-water_pH3_LS10	LÅ2 liq 24h 150ml methanol+MQ-water_pH3_LS10	LÅ2 liq 24h MQ waterLS10
Sampling Date		2023-04-04	2023-04-04	2023-04-04
Uppslutning		Ja	Ja	Ja
Extraktion		ja	ja	ja
Al, aluminium	µg/L	1470	987	39000
As, arsenik	µg/L	40,8	30	13
Ba, barium	µg/L	249	211	212
Ca, kalcium	mg/L	1350	1500	44
Cd, kadmium	µg/L	0,0986	0,0805	0,735
Co, kobolt	µg/L	21,8	31,7	14,4
Cr, krom	µg/L	6,94	2,58	49,6
Cu, koppar	µg/L	350	223	7220
Fe, järn	mg/L	80,9	189	43,4
Hg, kvicksilver	µg/L	0,0205	<0.02	0,51
K, kalium	mg/L	2750	68,2	59
Mg, magnesium	mg/L	180	182	77,3
Mn, mangan	µg/L	3910	4240	491
Mo, molybden	µg/L	1,45	2,99	38,4
Na, natrium	mg/L	931	852	692
Ni, nickel	µg/L	79	129	36,2
Pb, bly	µg/L	4,82	4,5	102
V, vanadin	µg/L	4,59	9,98	81,4
Zn, zink	µg/L	44000	71100	9670
MBT, monobutyltenn	ng/L	20,8	19,1	325
DBT, dibutyltenn	ng/L	134	240	2630
TBT, tributyltenn	ng/L	327	6730	8260

Table F. 3: Traffic runoff sediment after leaching phase 2.



ELEMENT	SAMPLE	Gå2 sed 24h 150ml Soap + 150 methanol + MQ waterLS10 pH3	Gå2 sed 24h 150ml Methanol + MQ waterLS10 pH3	Gå2 sed 24h MQ waterLS10
Sampling Date		2023-03-23	2023-03-23	2023-03-23
Torkning		Ja	Ja	Ja
Siktning/mortling		Ja	Ja	Ja
Uppslutning		Ja	Ja	Ja
Uppslutning AR		Ja	Ja	Ja
As, arsenik	mg/kg TS	1,31	1,29	1,35
Ba, barium	mg/kg TS	169	190	189
Cd, kadmium	mg/kg TS	0,137	0,164	0,17
Co, kobolt	mg/kg TS	15,6	17,4	21,6
Cr, krom	mg/kg TS	37,3	42,3	34,6
Cu, koppar	mg/kg TS	95,1	112	98,2
Hg, kvicksilver	mg/kg TS	<0.2	<0.2	<0.2
Ni, nickel	mg/kg TS	20,8	25,1	28,2
Pb, bly	mg/kg TS	16,7	19,4	16,4
V, vanadin	mg/kg TS	64,5	73,5	74
Zn, zink	mg/kg TS	388	430	526
Ag, silver	mg/kg TS	<0.05	0,107	<0.05
Mo, molybden	mg/kg TS	2,67	4,62	3,98
Sb, antimon	mg/kg TS	4,27	8,5	5,94
Sn, tenn	mg/kg TS	12,2	21,8	17,5
alifater >C5-C8	mg/kg TS	<10.0	<10.0	<10.0
alifater >C8-C10	mg/kg TS	<10.0	<10.0	<10.0
alifater >C10-C12	mg/kg TS	22	<20	<20
alifater >C12-C16	mg/kg TS	51	52	42
alifater >C5-C16	mg/kg TS	73	52	42
alifater >C16-C35	mg/kg TS	13300	4560	4030
aromater >C8-C10	mg/kg TS	<56.7	<0.480	<0.480
aromater >C10-C16	mg/kg TS	0,581	0,524	0,438
metylpyrener/metylfluorantener	mg/kg TS	<12.2	1,8	1,5
metylkrysener/metylbens(a)antracener	mg/kg TS	2,4	2,8	2,6
aromater >C16-C35	mg/kg TS	2,4	4,6	4,1
bensen	mg/kg TS	<0.018	<0.016	<0.015
toluen	mg/kg TS	0,122	0,142	<0.074
etylbensen	mg/kg TS	<0.088	<0.078	<0.074
summa xylener	mg/kg TS	<0.088	<0.078	<0.074
summa TEX	mg/kg TS	0,12	0,14	<0.15
naftalen	mg/kg TS	0,08	0,021	0,072
acenaftylen	mg/kg TS	0,03	0,01	<0.010
acenaften	mg/kg TS	0,015	0,014	0,02
fluoren	mg/kg TS	0,045	0,032	0,036
fenantren	mg/kg TS	0,475	0,271	0,238
antracen	mg/kg TS	0,0588	0,0341	0,0265
fluoranten	mg/kg TS	0,757	0,406	0,322
pyren	mg/kg TS	1,26	0,628	0,423
bens(a)antracen	mg/kg TS	0,206	0,109	0,088
krysen	mg/kg TS	0,545	0,253	0,16
bens(b)fluoranten	mg/kg TS	0,466	0,251	0,141
bens(k)fluoranten	mg/kg TS	0,119	0,065	0,039
bens(a)pyren	mg/kg TS	0,354	0,147	0,108
Indeno(123cd)pyren	mg/kg TS	0,224	0,08	0,065
dibens(a,h)antracen	mg/kg TS	0,101	0,049	0,048
bens(g,h,i)perylen	mg/kg TS	0,484	0,238	0,173
summa PAH 16	mg/kg TS	5,22	2,61	1,96
Summa PAH 11	mg/kg TS	4,95	2,48	1,78
summa cancerogena PAH	mg/kg TS	2,02	0,954	0,649
summa övriga PAH	mg/kg TS	3,2	1,65	1,31
summa PAH L	mg/kg TS	0,125	0,045	0,092
summa PAH M	mg/kg TS	2,6	1,37	1,04
summa PAH H	mg/kg TS	2,5	1,19	0,822
torrsubstans vid 105°C	%	38,4	39,3	46,4
TOC	% TS	16,4	10,8	12,3

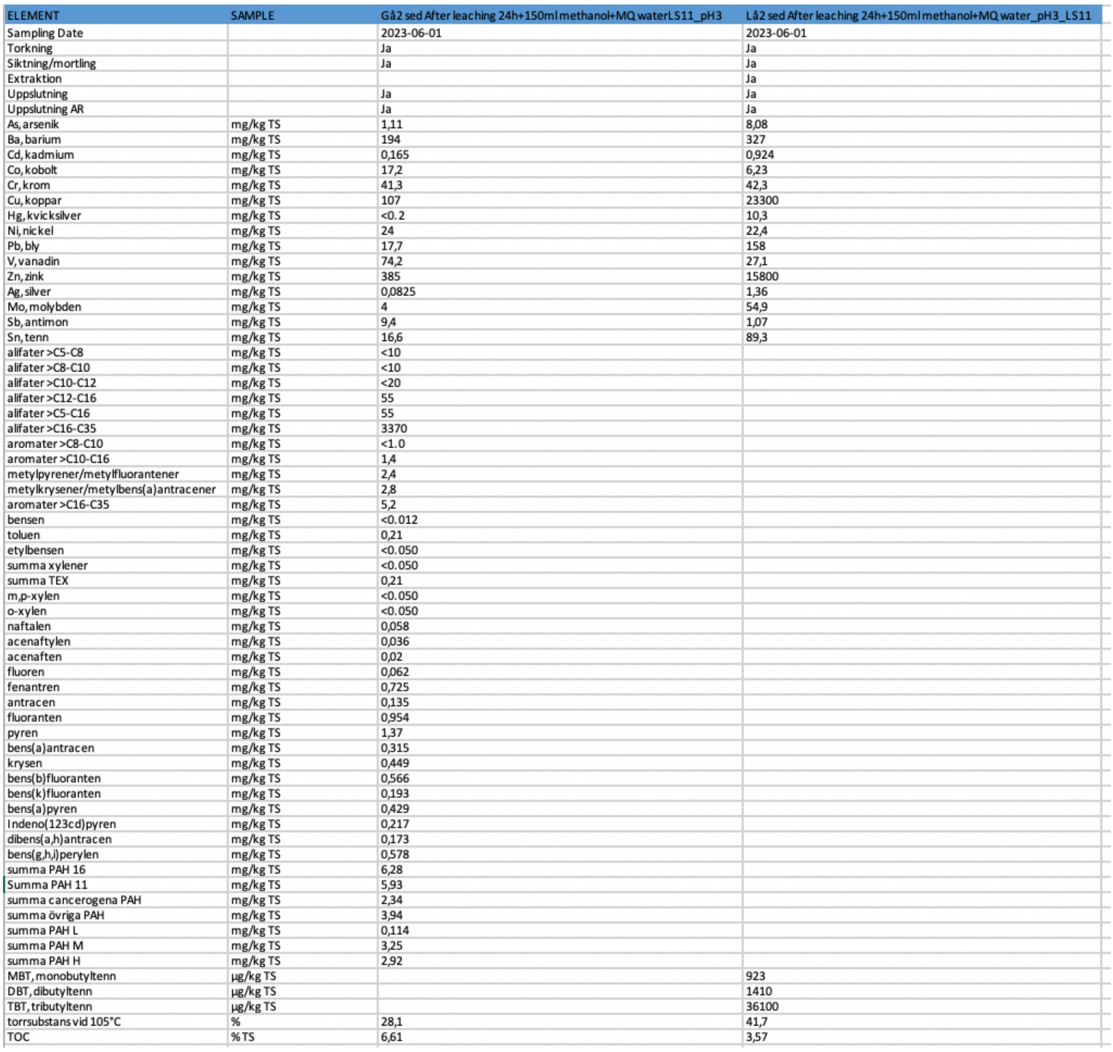
Table F. 4: Traffic runoff leachate water after leaching phase 2.



ELEMENT	SAMPLE	Gå2 liq24h 150ml Soap+150 methanol+MQ waterLS10 pH3	Gå2 liq 150ml Soap+methanol+MQ waterLS10	Gå liq MQ waterL S10
Sampling Date		2023-03-24	2023-03-24	2023-03-24
Uppslutning		Ja	Ja	Ja
Al, aluminium	µg/L	44100	34100	31300
As, arsenik	µg/L	18,6	10,2	6,59
Ba, barium	µg/L	2460	6340	1320
Ca, kalcium	mg/L	561	484	121
Cd, kadmium	µg/L	3,16	3,99	1,12
Co, kobolt	µg/L	1360	1280	148
Cr, krom	µg/L	176	114	155
Cu, koppar	µg/L	751	737	1460
Fe, järn	mg/L	180	222	75,2
Hg, kvicksilver	µg/L	0,11	0,0801	0,0954
K, kalium	mg/L	2490	22,7	27,3
Mg, magnesium	mg/L	97,8	58,3	21,5
Mn, mangan	µg/L	14700	14200	3140
Mo, molybden	µg/L	20,7	17,8	37,8
Na, natrium	mg/L	299	146	154
Ni, nickel	µg/L	519	520	92,1
Pb, bly	µg/L	71,3	61,6	139
V, vanadin	µg/L	186	100	129
Zn, zink	µg/L	42000	28400	4210
naftalen	µg/L	<0.120	0,139	0,13
acenaftylen	µg/L	<0.010	<0.010	<0.020
acenaften	µg/L	<0.040	<0.060	<0.050
fluoren	µg/L	<0.130	<0.120	<0.120
fenantren	µg/L	0,861	0,771	0,968
antracen	µg/L	0,084	0,094	0,112
fluoranten	µg/L	1,1	1,13	1,6
pyren	µg/L	<1.71	1,89	2,68
bens(a)antracen	µg/L	<0.290	0,36	0,516
krysen	µg/L	<0.860	0,601	0,882
bens(b)fluoranten	µg/L	<0.610	<0.790	<1.32
bens(k)fluoranten	µg/L	<0.140	<0.130	<0.280
bens(a)pyren	µg/L	<0.240	<0.430	<0.600
dibens(a,h)antracen	µg/L	<0.110	<0.200	<0.280
bens(g,h,i)perylen	µg/L	0,592	0,915	1,4
indeno(1,2,3,cd)pyren	µg/L	<0.230	<0.350	<0.610
summa PAH 16	µg/L	2,64	5,9	8,29
summa cancerogena PAH	µg/L	<1.24	0,961	1,4
summa övriga PAH	µg/L	2,64	4,94	6,89
summa PAH L	µg/L	<0.0850	0,139	0,13
summa PAH M	µg/L	2,04	3,88	5,36
summa PAH H	µg/L	0,592	1,88	2,8

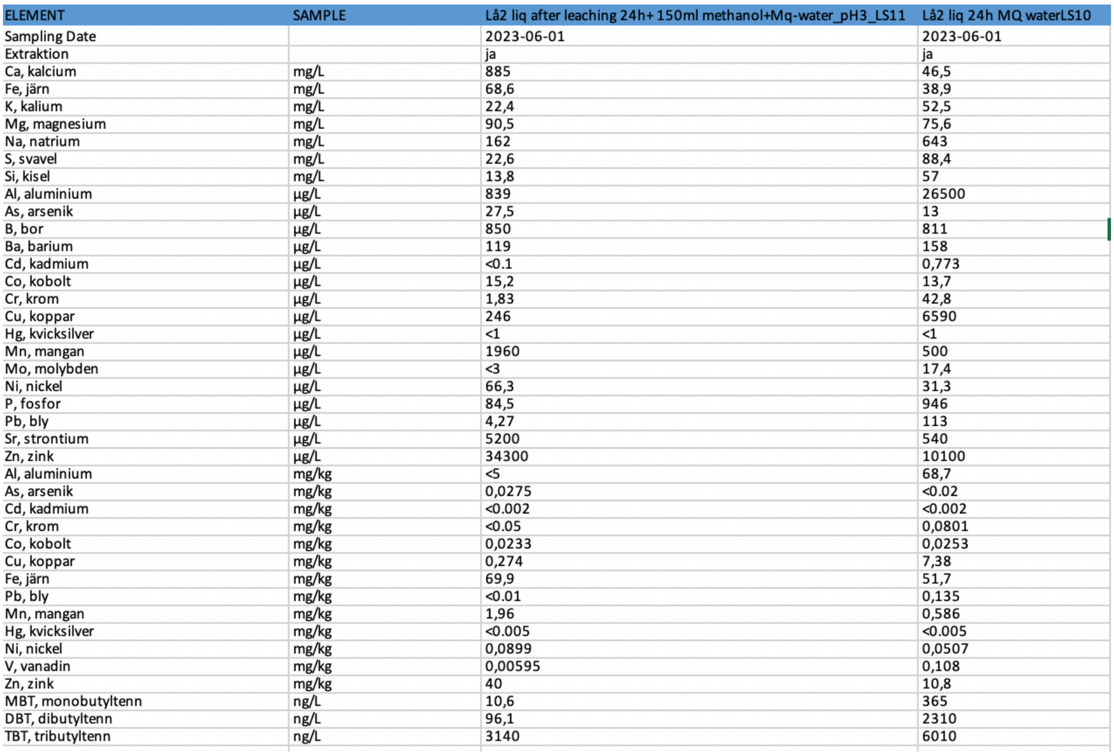
Appendix G: Phase 3 original results from ALS Scandinavian AB

Table G. 1: Marina and Traffic runoff sediment after leaching phase 3.



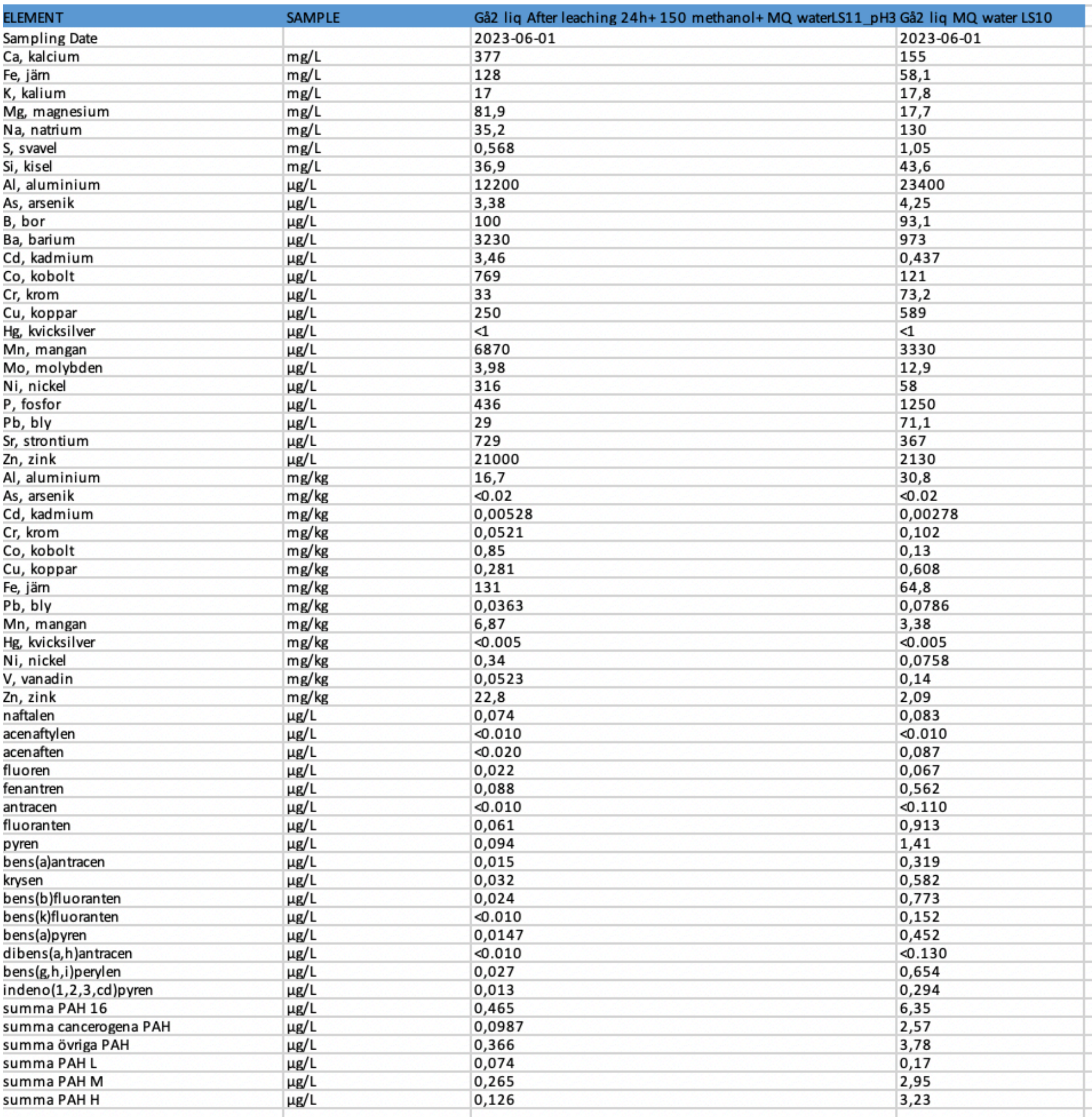
ELEMENT	SAMPLE	Gå2 sed After leaching 24h+150ml methanol+MQ waterLS11_pH3	Lå2 sed After leaching 24h+150ml methanol+MQ water_pH3_LS11
Sampling Date		2023-06-01	2023-06-01
Torkning		Ja	Ja
Siktning/mortling		Ja	Ja
Extraktion			Ja
Uppslutning		Ja	Ja
Uppslutning AR		Ja	Ja
As, arsenik	mg/kg TS	1,11	8,08
Ba, barium	mg/kg TS	194	327
Cd, kadmium	mg/kg TS	0,165	0,924
Co, kobolt	mg/kg TS	17,2	6,23
Cr, krom	mg/kg TS	41,3	42,3
Cu, koppar	mg/kg TS	107	23300
Hg, kvicksilver	mg/kg TS	<0.2	10,3
Ni, nickel	mg/kg TS	24	22,4
Pb, bly	mg/kg TS	17,7	158
V, vanadin	mg/kg TS	74,2	27,1
Zn, zink	mg/kg TS	385	15800
Ag, silver	mg/kg TS	0,0825	1,36
Mo, molybden	mg/kg TS	4	54,9
Sb, antimon	mg/kg TS	9,4	1,07
Sn, tenn	mg/kg TS	16,6	89,3
alifater >C5-C8	mg/kg TS	<10	
alifater >C8-C10	mg/kg TS	<10	
alifater >C10-C12	mg/kg TS	<20	
alifater >C12-C16	mg/kg TS	55	
alifater >C5-C16	mg/kg TS	55	
alifater >C16-C35	mg/kg TS	3370	
aromater >C8-C10	mg/kg TS	<1.0	
aromater >C10-C16	mg/kg TS	1,4	
metylpyrener/metylfluorantener	mg/kg TS	2,4	
metylkrysener/metylbens(a)antracener	mg/kg TS	2,8	
aromater >C16-C35	mg/kg TS	5,2	
bensen	mg/kg TS	<0.012	
toluen	mg/kg TS	0,21	
etylbensen	mg/kg TS	<0.050	
summa xylener	mg/kg TS	<0.050	
summa TEX	mg/kg TS	0,21	
m,p-xylen	mg/kg TS	<0.050	
o-xylen	mg/kg TS	<0.050	
naftalen	mg/kg TS	0,058	
acenaftylen	mg/kg TS	0,036	
acenaften	mg/kg TS	0,02	
fluoren	mg/kg TS	0,062	
fenantren	mg/kg TS	0,725	
antracen	mg/kg TS	0,135	
fluoranten	mg/kg TS	0,954	
pyren	mg/kg TS	1,37	
bens(a)antracen	mg/kg TS	0,315	
krysen	mg/kg TS	0,449	
bens(b)fluoranten	mg/kg TS	0,566	
bens(k)fluoranten	mg/kg TS	0,193	
bens(a)pyren	mg/kg TS	0,429	
Indeno(123cd)pyren	mg/kg TS	0,217	
dibens(a,h)antracen	mg/kg TS	0,173	
bens(g,h,i)perylen	mg/kg TS	0,578	
summa PAH 16	mg/kg TS	6,28	
Summa PAH 11	mg/kg TS	5,93	
summa cancerogena PAH	mg/kg TS	2,34	
summa övriga PAH	mg/kg TS	3,94	
summa PAH L	mg/kg TS	0,114	
summa PAH M	mg/kg TS	3,25	
summa PAH H	mg/kg TS	2,92	
MBT, monobutyltenn	µg/kg TS		923
DBT, dibutyltenn	µg/kg TS		1410
TBT, tributyltenn	µg/kg TS		36100
torrsubstans vid 105°C	%	28,1	41,7
TOC	% TS	6,61	3,57

Table G. 2: Marina leachate water after leaching phase 3.



ELEMENT	SAMPLE	Lå2 liq after leaching 24h+ 150ml methanol+Mq-water_pH3_LS11	Lå2 liq 24h MQ waterLS10
Sampling Date		2023-06-01	2023-06-01
Extraktion		ja	ja
Ca, kalcium	mg/L	885	46,5
Fe, järn	mg/L	68,6	38,9
K, kalium	mg/L	22,4	52,5
Mg, magnesium	mg/L	90,5	75,6
Na, natrium	mg/L	162	643
S, svavel	mg/L	22,6	88,4
Si, kisel	mg/L	13,8	57
Al, aluminium	µg/L	839	26500
As, arsenik	µg/L	27,5	13
B, bor	µg/L	850	811
Ba, barium	µg/L	119	158
Cd, kadmium	µg/L	<0.1	0,773
Co, kobolt	µg/L	15,2	13,7
Cr, krom	µg/L	1,83	42,8
Cu, koppar	µg/L	246	6590
Hg, kvicksilver	µg/L	<1	<1
Mn, mangan	µg/L	1960	500
Mo, molybden	µg/L	<3	17,4
Ni, nickel	µg/L	66,3	31,3
P, fosfor	µg/L	84,5	946
Pb, bly	µg/L	4,27	113
Sr, strontium	µg/L	5200	540
Zn, zink	µg/L	34300	10100
Al, aluminium	mg/kg	<5	68,7
As, arsenik	mg/kg	0,0275	<0.02
Cd, kadmium	mg/kg	<0.002	<0.002
Cr, krom	mg/kg	<0.05	0,0801
Co, kobolt	mg/kg	0,0233	0,0253
Cu, koppar	mg/kg	0,274	7,38
Fe, järn	mg/kg	69,9	51,7
Pb, bly	mg/kg	<0.01	0,135
Mn, mangan	mg/kg	1,96	0,586
Hg, kvicksilver	mg/kg	<0.005	<0.005
Ni, nickel	mg/kg	0,0899	0,0507
V, vanadin	mg/kg	0,00595	0,108
Zn, zink	mg/kg	40	10,8
MBT, monobutyltenn	ng/L	10,6	365
DBT, dibutyltenn	ng/L	96,1	2310
TBT, tributyltenn	ng/L	3140	6010

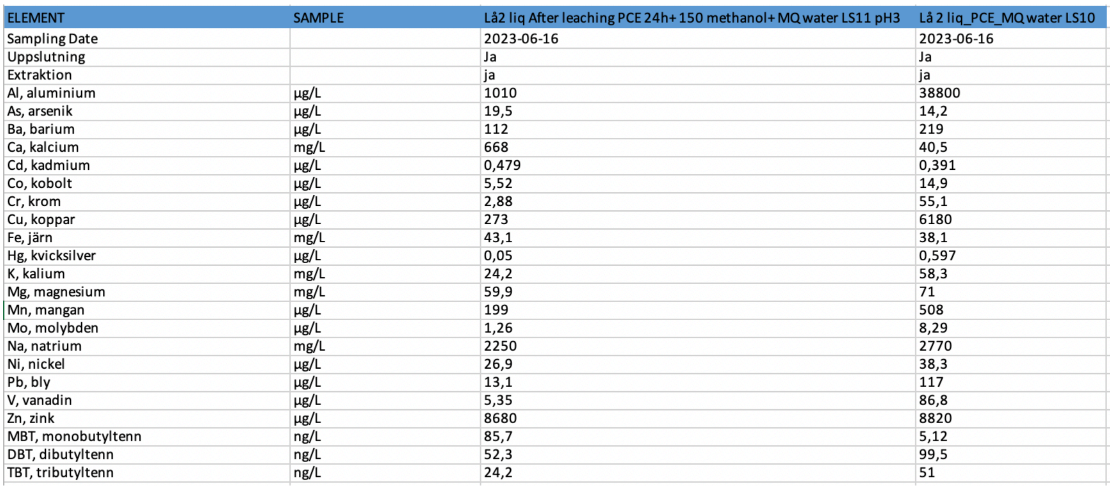
Table G. 3: Traffic runoff leachate water after leaching phase 3.



ELEMENT	SAMPLE	Gå2 liq After leaching 24h+ 150 methanol+ MQ waterLS11_pH3	Gå2 liq MQ water LS10
Sampling Date		2023-06-01	2023-06-01
Ca, kalcium	mg/L	377	155
Fe, järn	mg/L	128	58,1
K, kalium	mg/L	17	17,8
Mg, magnesium	mg/L	81,9	17,7
Na, natrium	mg/L	35,2	130
S, svavel	mg/L	0,568	1,05
Si, kisel	mg/L	36,9	43,6
Al, aluminium	µg/L	12200	23400
As, arsenik	µg/L	3,38	4,25
B, bor	µg/L	100	93,1
Ba, barium	µg/L	3230	973
Cd, kadmium	µg/L	3,46	0,437
Co, kobolt	µg/L	769	121
Cr, krom	µg/L	33	73,2
Cu, koppar	µg/L	250	589
Hg, kvicksilver	µg/L	<1	<1
Mn, mangan	µg/L	6870	3330
Mo, molybden	µg/L	3,98	12,9
Ni, nickel	µg/L	316	58
P, fosfor	µg/L	436	1250
Pb, bly	µg/L	29	71,1
Sr, strontium	µg/L	729	367
Zn, zink	µg/L	21000	2130
Al, aluminium	mg/kg	16,7	30,8
As, arsenik	mg/kg	<0.02	<0.02
Cd, kadmium	mg/kg	0,00528	0,00278
Cr, krom	mg/kg	0,0521	0,102
Co, kobolt	mg/kg	0,85	0,13
Cu, koppar	mg/kg	0,281	0,608
Fe, järn	mg/kg	131	64,8
Pb, bly	mg/kg	0,0363	0,0786
Mn, mangan	mg/kg	6,87	3,38
Hg, kvicksilver	mg/kg	<0.005	<0.005
Ni, nickel	mg/kg	0,34	0,0758
V, vanadin	mg/kg	0,0523	0,14
Zn, zink	mg/kg	22,8	2,09
naftalen	µg/L	0,074	0,083
acenaftylen	µg/L	<0.010	<0.010
acenaften	µg/L	<0.020	0,087
fluoren	µg/L	0,022	0,067
fenantren	µg/L	0,088	0,562
antracen	µg/L	<0.010	<0.110
fluoranten	µg/L	0,061	0,913
pyren	µg/L	0,094	1,41
bens(a)antracen	µg/L	0,015	0,319
krysen	µg/L	0,032	0,582
bens(b)fluoranten	µg/L	0,024	0,773
bens(k)fluoranten	µg/L	<0.010	0,152
bens(a)pyren	µg/L	0,0147	0,452
dibens(a,h)antracen	µg/L	<0.010	<0.130
bens(g,h,i)perylen	µg/L	0,027	0,654
indeno(1,2,3,cd)pyren	µg/L	0,013	0,294
summa PAH 16	µg/L	0,465	6,35
summa cancerogena PAH	µg/L	0,0987	2,57
summa övriga PAH	µg/L	0,366	3,78
summa PAH L	µg/L	0,074	0,17
summa PAH M	µg/L	0,265	2,95
summa PAH H	µg/L	0,126	3,23

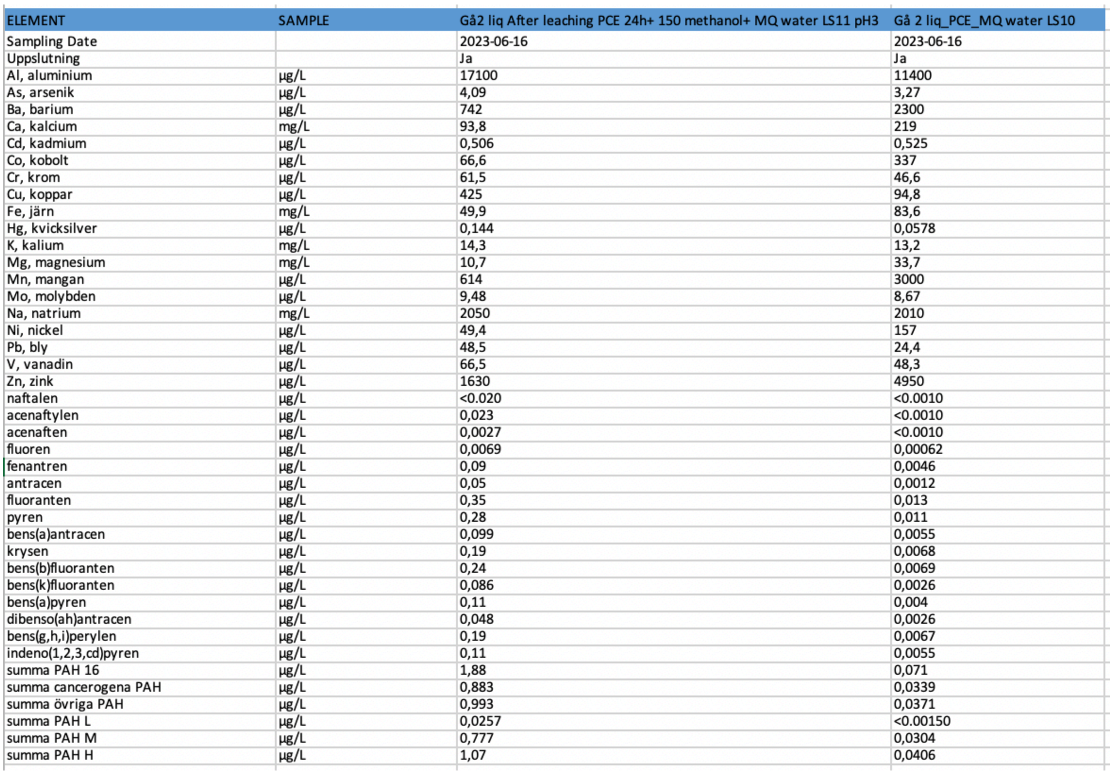
Appendix H: Original results after PEC from ALS Scandinavian AB

Table H. 1: Marina leachate water after PEC treatment



ELEMENT	SAMPLE	Lå2 liq After leaching PCE 24h+ 150 methanol+ MQ water LS11 pH3	Lå 2 liq_PCE_MQ water LS10
Sampling Date		2023-06-16	2023-06-16
Uppslutning		Ja	Ja
Extraktion		ja	ja
Al, aluminium	µg/L	1010	38800
As, arsenik	µg/L	19,5	14,2
Ba, barium	µg/L	112	219
Ca, kalcium	mg/L	668	40,5
Cd, kadmium	µg/L	0,479	0,391
Co, kobolt	µg/L	5,52	14,9
Cr, krom	µg/L	2,88	55,1
Cu, koppar	µg/L	273	6180
Fe, järn	mg/L	43,1	38,1
Hg, kvicksilver	µg/L	0,05	0,597
K, kalium	mg/L	24,2	58,3
Mg, magnesium	mg/L	59,9	71
Mn, mangan	µg/L	199	508
Mo, molybden	µg/L	1,26	8,29
Na, natrium	mg/L	2250	2770
Ni, nickel	µg/L	26,9	38,3
Pb, bly	µg/L	13,1	117
V, vanadin	µg/L	5,35	86,8
Zn, zink	µg/L	8680	8820
MBT, monobutyltenn	ng/L	85,7	5,12
DBT, dibutyltenn	ng/L	52,3	99,5
TBT, tributyltenn	ng/L	24,2	51

Table H. 2: Traffic runoff leachate water after PEC treatment



ELEMENT	SAMPLE	Gå2 liq After leaching PCE 24h+ 150 methanol+ MQ water LS11 pH3	Gå 2 liq_PCE_MQ water LS10
Sampling Date		2023-06-16	2023-06-16
Uppslutning		Ja	Ja
Al, aluminium	µg/L	17100	11400
As, arsenik	µg/L	4,09	3,27
Ba, barium	µg/L	742	2300
Ca, kalcium	mg/L	93,8	219
Cd, kadmium	µg/L	0,506	0,525
Co, kobolt	µg/L	66,6	337
Cr, krom	µg/L	61,5	46,6
Cu, koppar	µg/L	425	94,8
Fe, järn	mg/L	49,9	83,6
Hg, kvicksilver	µg/L	0,144	0,0578
K, kalium	mg/L	14,3	13,2
Mg, magnesium	mg/L	10,7	33,7
Mn, mangan	µg/L	614	3000
Mo, molybden	µg/L	9,48	8,67
Na, natrium	mg/L	2050	2010
Ni, nickel	µg/L	49,4	157
Pb, bly	µg/L	48,5	24,4
V, vanadin	µg/L	66,5	48,3
Zn, zink	µg/L	1630	4950
naftalen	µg/L	<0.020	<0.0010
acenaftylen	µg/L	0,023	<0.0010
acenaften	µg/L	0,0027	<0.0010
fluoren	µg/L	0,0069	0,00062
fenantren	µg/L	0,09	0,0046
antracen	µg/L	0,05	0,0012
fluoranten	µg/L	0,35	0,013
pyren	µg/L	0,28	0,011
bens(a)antracen	µg/L	0,099	0,0055
krysen	µg/L	0,19	0,0068
bens(b)fluoranten	µg/L	0,24	0,0069
bens(k)fluoranten	µg/L	0,086	0,0026
bens(a)pyren	µg/L	0,11	0,004
dibenso(ah)antracen	µg/L	0,048	0,0026
bens(g,h,i)perylen	µg/L	0,19	0,0067
indeno(1,2,3,cd)pyren	µg/L	0,11	0,0055
summa PAH 16	µg/L	1,88	0,071
summa cancerogena PAH	µg/L	0,883	0,0339
summa övriga PAH	µg/L	0,993	0,0371
summa PAH L	µg/L	0,0257	<0.00150
summa PAH M	µg/L	0,777	0,0304
summa PAH H	µg/L	1,07	0,0406