Interreg
Co-funded by
the European Union

Central Baltic Programme

StoPWa

Leachate quality of stormwater filter materials made of construction and demolition waste (CDW) by agglomeration in StoPWa project

Project identification

Project number	CB0100091
Project name	Stormwater purification with construction and demolition waste
Project acronym	StoPWa

Report identification

Reporting period	Period 4
Activity / Deliverable number	
Type of report	Scientific report
Date of report	10.3.2025
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Abstract

StoPWa project aims to develop and test stormwater filtration systems utilizing construction and demolition waste (CDW) as filter material. Fine-grade CDW residue is processed into aggregates of selected size fraction using agglomeration. The porous CDW agglomerates have a high potential to adsorb contaminants from stormwater. To ensure an environmentally safe use of CDW materials in the stormwater filter, leaching tests of agglomerated materials were carried out in the laboratories of UH and TalTech. The leachate concentrations of nutrients, DOC and soluble metals were analysed from two size fractions of agglomerated filter material in repeated tests. The measured nitrogen and phosphorus levels were rather high in comparison with some recently proposed guidelines, whereas the concentrations of heavy metals were comparable or below the guideline values. In conclusion, the filter material was found to release nutrients and metals on exposure to tap water. The leachate levels decreased considerable in repeated leachings, but the material is likely to act as a source of nutrients at least in the beginning of its use. It is hypothesized that biofilms and subsequent biological removal of nutrients will develop in the filter material when applied in field conditions.

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1 Background

The Interreg Central Baltic project 'Stormwater purification with construction and demolition waste' (StoPWa) develops and tests stormwater filtration systems utilizing construction and demolition waste (CDW) as filter material. The goal of StoPWa project is to develop a stormwater filter that would purify stormwater in selected locations by mechanical and biofiltration. The filter prototypes will be tested both in laboratory environments and in field tests where full scale stormwater filters will be constructed in three cities. The main expected results are increased recycling rate of CDW and reduced runoff pollution burden to water bodies by stormwater contaminants.

The raw CDW material needs to be processed before it can be used as stormwater filtering media. In StoPWa project, fine-grade CDW residue is processed into granules / aggregates of selected size fraction using agglomeration (Chapter 2.1). These aggregates can be applied in stormwater treatment arrangements to replace more commonly used natural aggregates such as sand and gravel. The porous CDW agglomerates have a high potential to adsorb contaminants from stormwater.

CDW fractions may carry contaminants that can leach out when in contact with stormwater. To ensure an environmentally safe use of CDW materials in the stormwater filter, leaching tests of agglomerated filter materials were carried out. The results of leaching tests of raw CDW materials have been presented in a previous report.

This report presents results of leaching tests of agglomerated CDSW materials that were carried out in laboratory setups in the University of Helsinki (UH) and in Tallinn University of Technology (TalTech).

2 Materials and methods

2.1 Description of agglomerated CDW

Agglomeration is defined as a process of accumulating fine material into cohesive units such as pellets or granules. In general, particles can stick together to form aggregates in different ways: physical or chemical forces between individual particles, adhered binders on the solid surfaces that form a material bridge, or chemical or physical modifications of the solids. In this report, the aim of agglomeration process was to form aggregates of desired size out of fine-grade CDW material.

Figure 1. A sample of agglomerated CDW aggregates, granule size >5 mm.

The materials used in agglomeration were miscellaneous construction and demolition waste (CDW, 80% of weight) and plastic waste (LDPE, 20%). CDW was acquired from a demolition company and LDPE from a waste management company in Lahti, Finland. The agglomeration process was done in the laboratory of Fiber Composites in LUT University. The materials were first crushed into particle size fraction of 0-10 mm. The materials were mixed in a closed high shear mixer/mill, where friction causes the mixture to heat up to 100-200 °C. Heat together with mixing causes particles to form aggregates in a specific process, which may involve sintering, partial melting or crystalization. The process may take several hours to complete. The formed aggregates are firm and solid and can then be sieved into desired size fractions (Figure 1).

2.2 Leaching test methods, UH

The leaching experiments were conducted in columns filled with 500 mL of loose agglomerates P1 or P2 (with three replicates) or with a filter made from the agglomerate material bound in a concrete matrix, F1, F2 or F3 (Table 1). The filters were wrapped in plastic film to make sure the water would flow through the filters rather than along the inside wall of the column. An equal mass of the same plastic wrap was also used in the control column, but since it did not leach measurable amounts of nutrients or metals its results are not included in the comparison presented here.

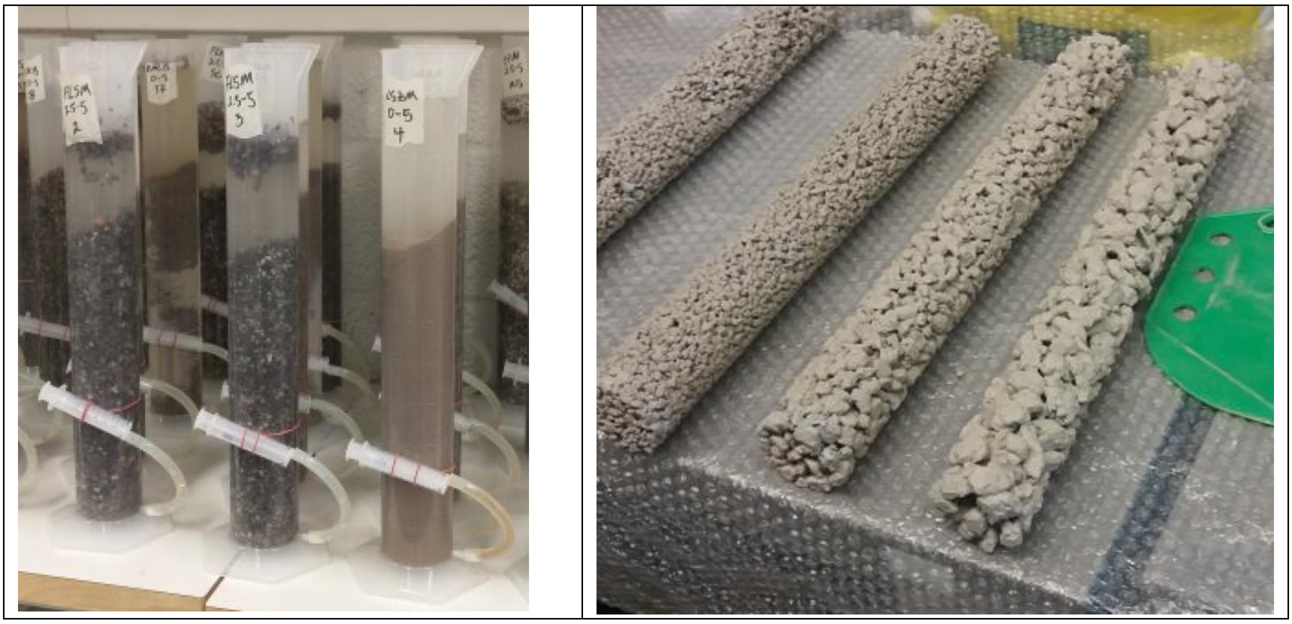


Figure 2. Test columns on the left and filter cassettes on the right.

Table 1. Size and type of the agglomerates and filters used in the comparison.

Sample	**Sample type**	**Diameter of agglomerates**
P1	Agglomerate AggP	> 4 mm
P2	Agglomerate AggP	0–4 mm
F1	Filter made from agglomerates (mass = 940 g)	8–14 mm
F2	Filter made from agglomerates (mass = 875 g)	> 8 mm
F3	Filter made from agglomerates (mass = 950 g)	4–8 mm

Table 2. Methods used by ALS in analysis of the agglomerate and filter leachates.

Parameter	**Method code**	**Description**
Chloride and Floride	CSN EN ISO 10304-1	Determination of dissolved fluoride, chloride, nitrite, bromide, nitrate and sulphate by ion liquid chromatography and calculation of nitrite nitrogen and nitrate nitrogen and sulphate sulphur from measured values including the calculation of total mineralization.
DOC	CSN EN ISO 20236, SM 5310, EN 1484	Determination of total organic carbon (TOC), dissolved organic carbon (DOC), total inorganic carbon (TIC) and total carbon (TC) by IR detection.
TOC	CSN EN ISO 20236, SM 5310	Determination of total organic carbon (TOC), dissolved organic carbon (DOC), total inorganic carbon (TIC) and total carbon (TC) by IR detection.
Dissolved Hg	US EPA Method 245.7, CSN EN ISO 17852	Determination of Mercury by Fluorescence Spectrometry. Sample was filtered by microfilter with porosity 0.45 µm followed by nitric acid addition prior to analysis.
Total Hg	US EPA Method 245.7, CSN EN ISO 17852	Determination of Mercury by Fluorescence Spectrometry. Sample was fixed by nitric acid addition prior to analysis.
Dissolved Metals	US EPA Method 200.8, CSN EN ISO 17294-2, US EPA Method 6020A, CSN 75 7358	Determination of elements by mass spectrometry with inductively coupled plasma and stoichiometric calculations of compounds concentration from measured values including the calculation of total mineralization and calculating the sum of Ca +Mg. Sample was filtered by microfilter with porosity 0.45 µm followed by nitric acid addition prior to analysis.
Total Metals	US EPA Method 200.8, CSN EN ISO 17294-2, US EPA Method 6020A, CSN 75 7358	Determination of elements by mass spectrometry with inductively coupled plasma and stoichiometric calculations of compounds concentration from measured values including the calculation of total mineralization and calculating the sum of Ca +Mg. Sample was fixed by nitric acid addition prior to analysis.
Total N	CSN EN ISO 20236	Determination of bound nitrogen (TNb) after oxidation to nitrogen oxides by chemiluminiscence detection.
Total Phosphorus	CSN EN ISO 6878 and CSN ISO 15681-1	Determination of total phosphorus by discrete spectrophotometry and calculation of phosphorus as P2O5 andPO43-from measured values.
Sulfate	CSN EN ISO 10304-1	Determination of dissolved fluoride, chloride, nitrite, bromide, nitrate and sulphate by ion liquid chromatography and calculation of nitrite nitrogen and nitrate nitrogen and sulphate sulphur from measured values including the calculation of total mineralization.

The columns were saturated with tap water (volume 406 ml for the agglomerate tests and 600 ml for the filter test) and drained after three days (appr. 72 h) of settling. This saturation-settling-and-draining process was repeated a total of three times for both the agglomerate and filter tests (referred to as leachings 1, 2 and 3 in this document). The pH of the leachates (Table 6) was analyzed at the University of Helsinki's Environmental

Laboratories in Lahti while the commercial laboratory ALS analysed the concentration of nutrients and metals. The specific methods used by ALS for each parameter are presented in Table 2.

2.3. Leaching test methods, TalTech

A series of leaching tests were carried out using laboratory scale reactors filled with the agglomerates to be tested (Figure 3) at the Environmental Technology Laboratory of the Department of Materials and Environmental Technology (TalTech).

Operating information for all reactors during the leaching experiment series is presented in Table 3. During each leaching test, the reactors were filled with tap water and allowed to leach for a pre-selected time. The specific leaching duration for each test is shown in Table 4. The reactors were then completely emptied by gravity drainage and the collected leachate samples were analyzed for numerous water quality parameters (Table 5). Clean tap water was used as control in the analyses.

Table 3. Operational information on laboratory scale reactors for a series of leaching experiments.

Reactor (R)	Agglomerates	Fraction, mm	Packed column weight, kg	Average tap water volume per leaching test, L
R1	AggP	<4	34	27.6
R2	AggP	<4/>4*	31.5	33.9
R3	AggP	>4	27.6	40.3

**ca 50/50*

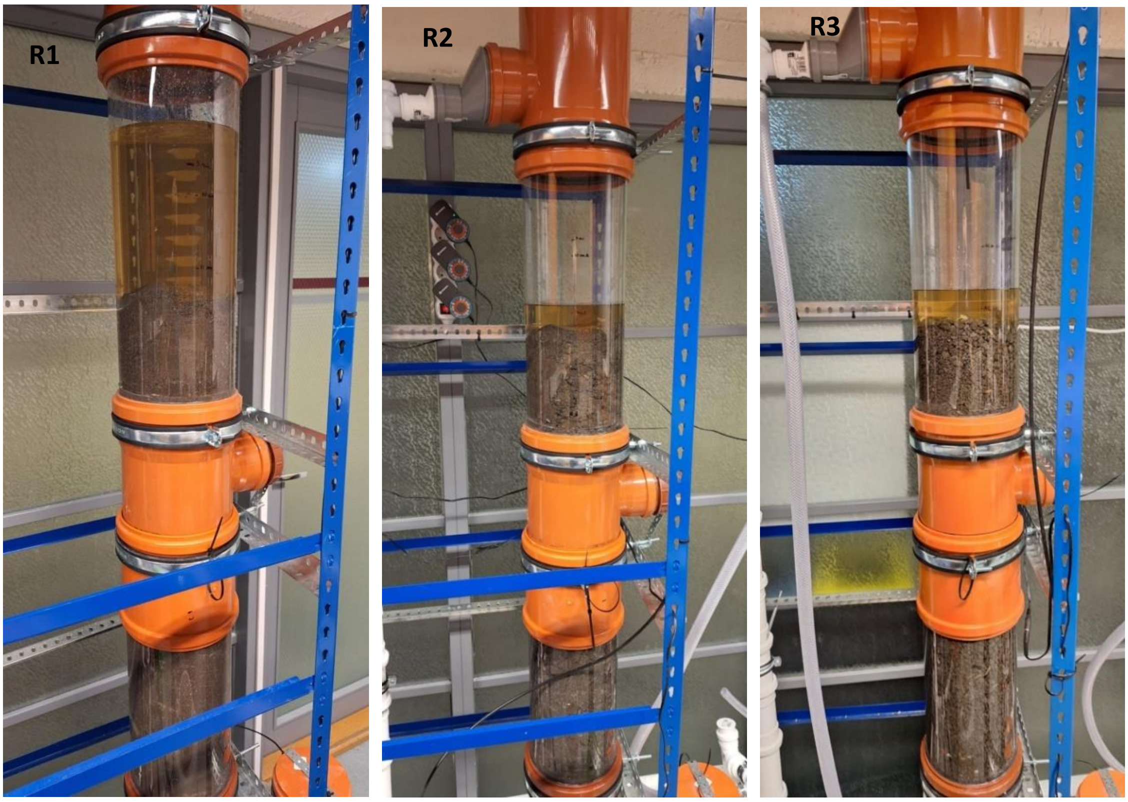


Figure 3. Laboratory scale reactors filled with agglomerates and tap water (leaching test L1): R1, R2 and R3.

Table 4. Specific leaching duration for each test in a series of leaching experiments.

Leaching (L) test nr	**Designation**	**Duration**	**Tap water volume, L**		
			R1	**R2**	**R3**
1	L1	15 min	38.3*	38.9	42
2	L2	15 min	24.7	34.7	40
3	L3	15 min	22.2	35.8	40.4
4	L4	24 h	29	33.4	40.2
5	L5	24 h	23.7	31.6	40
6	L6	24 h	30	32.5	40
7	L7	72 h	27	33	39.8
8	L8	72 h	26.8	33	39.7
9	L9	72 h	26.7	32.2	40

**slightly larger volume than average for this series due to the difficulty of wetting used AggP[<4 mm]*

Table 5. Water quality parameters analyzed/measured in leachate samples.

Parameter		**Unit**	**Analytical instrument/method**
Fluoride	F^-	mg/L	Ion chromatography with conductivity detector (IC-CD)
Sodium	Na^+	mg/L	IC-CD
Ammonium	NH_4^+	mg/L	IC-CD
Potassium	K^+	mg/L	IC-CD
Calcium	Ca^{2+}	mg/L	IC-CD
Magnesium	Mg^{2+}	mg/L	IC-CD
Arsenic*	As	µg/L	EVS-EN ISO 17294-2:2023 (Water quality - Application of inductively coupled plasma mass spectrometry (ICP-MS) - Part 2: Determination of selected elements including uranium isotopes)
Cadmium*	Cd	µg/L	EVS-EN ISO 17294-2:2023
Cobalt*	As	µg/L	EVS-EN ISO 17294-2:2023
Chromium*	Cr	µg/L	EVS-EN ISO 17294-2:2023
Nickel*	Ni	µg/L	EVS-EN ISO 17294-2:2023
Lead*	Pb	µg/L	EVS-EN ISO 17294-2:2023
Zinc*	Zn	µg/L	EVS-EN ISO 17294-2:2023
Copper*	Cu	µg/L	EVS-EN ISO 17294-2:2023
Mercury	As	µg/L	EVS-EN ISO 17852 (Water quality - Determination of mercury - Method using atomic fluorescence spectrometry)
Chloride	Cl^-	mg/L	IC-CD
Nitrite	NO_2^-	mg/L	IC-CD
Nitrate	NO_3^-	mg/L	IC-CD
Sulphate	SO_4^{2-}	mg/L	IC-CD
Phosphate	PO_4^{3-}	mg/L	IC-CD
DOC		mgC/L	Total Organic Carbon/Total Nitrogen (TOC/TN) analyzer
IC		mgC/L	TOC/TN analyzer
TN		mgN/L	TOC/TN analyzer
pH		-	pH-meter
EC		µS/cm	Electrical conductivity meter

**analyzed only from leachate sample L9 by a commercial laboratory (Eesti Keskkonnauuringute Keskus OÜ)*

The results of the analysis are presented as the mean value with a standard deviation of at least three parallel repetitions with an error of less than 5%.

3 Results

3.1 Results of leaching tests, UH

The pH of the leachates from the agglomerate filled columns was between 9.45 and 9.85 in the initial leaching, but was observed to drop significantly with each leaching, reaching values of 7.82 and 8.67 in P1 and P2, respectively, by the final round (Table 6). In leachates from the cement-bound agglomerate filter cassettes F1-F3, pH levels were significantly higher with measured values above 11.

Table 6. pH of agglomerate (P1, P2) and filter (F1...F3) leachates.

Sample	Leaching 1	Leaching 2	Leaching 3
P1	9.45 (± SE 0.16)	8.42 (± SE 0.11)	7.82 (± SE 0.01)
P2	9.85 (± SE 0.02)	9.31 (± SE 0.11)	8.67 (± SE 0.07)
F1	11.58	11.35	11.22
F2	11.40	11.20	11.31
F3	11.51	11.25	11.23

Nutrients

A considerable amount of nutrients leached from the agglomerates during testing. Concentrations of leachable nitrogen (N) (P1 and P2 in Figure 4) were found to be four to five times higher than the limit set for wastewater treatment plant discharges (7–10.5 mg/L, Finlex 365/1994) in the initial leachings, and decreasing to two to three times the limit by the final leaching.

Leachable phosphorous (P1 and P2 in Figure 5) from the agglomerates was found to exceed the limit set for wastewater discharges (0.8–1.6 mg/L, Finlex 365/1994) only in the first leaching from P2. Following the pattern observed with N, this value decreased with subsequent leachings, reaching a concentration of 0.42 mg/L in the third and final leachate sample.

A considerable amount of nutrients also leached from the concrete-bound filter cassettes during testing, though they were not as high as those observed from the unbound agglomerate materials. Concentrations of leachable nitrogen were found to exceed the limit set for wastewater treatment plant discharges (7–10.5 mg/L, Finlex 365/1994) in the initial and final leachings. Leachable phosphorous (F1–F3 in Figure 5) from the filters was found to exceed the limit set for wastewater discharges (0.8–1.6 mg/L, Finlex 365/1994) in the initial leachings, but decreasing to concentrations of 0.69–1.15 mg/L in the third and final leachate sample.

The concentration of leachable dissolved organic carbon (DOC) from the agglomerates was 2035 and 1153 mg/L in the first leachings, falling to 345 and 558 mg/L by the third (P1 and P2 in Figure 6). The initial concentration of leachable dissolved organic carbon (DOC) were markedly lower in the filter cassette leachates compared to the agglomerates, ranging from 857–541 mg/L and decreasing to 397–310 mg/L by the third leaching.

Notably, the observed decrease in nutrient concentrations in the filter cassettes were not as precipitous as those seen in the unbound agglomerates. This indicates that the cement binder acts as a regulator, slowing the release of nutrients.

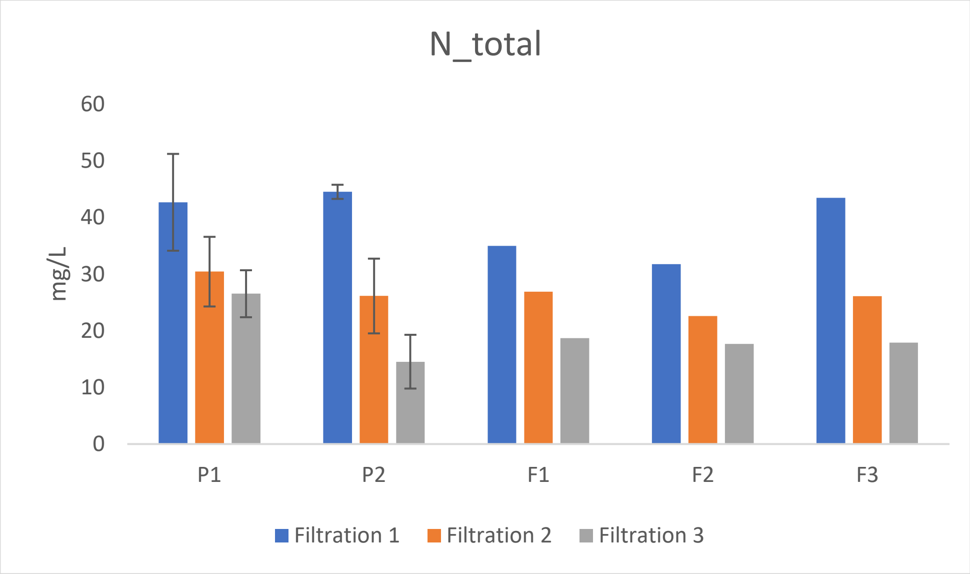


Figure 4. Concentration of total nitrogen (mg/L, ± SE) in the leachate of different CDW and agglomerates.

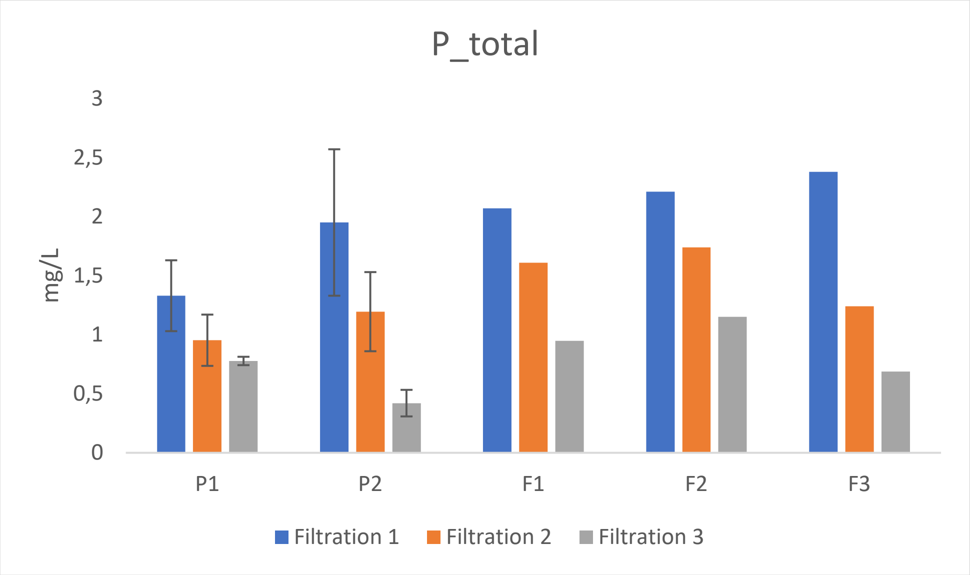


Figure 5. Concentration of total phosphorous (mg/L, ± SE) in the leachate of different CDW and agglomerates.

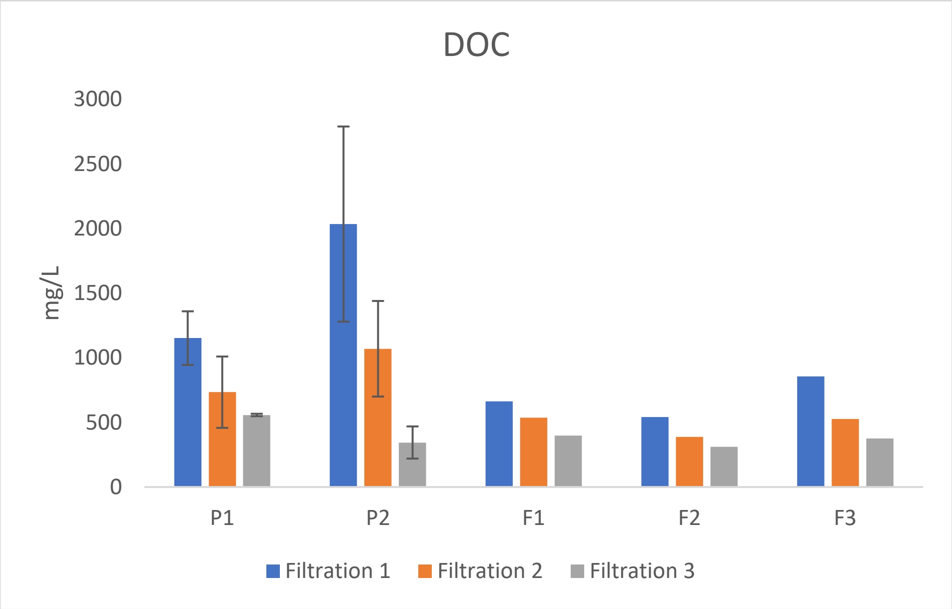


Figure 6. The concentration of dissolved organic carbon (mg/L, ± SE) in the leachate of different agglomerates (P1, P2) and filters (F1, F2, F3).

Metals

Calcium (Ca), magnesium (Mg), potassium (K), sodium (Na) and boron (B) were the most abundant metals in all the leachates (Figure 7 and Table A1), with Ca being the most abundant. Cadmium (Cd), nickel (Ni), lead (Pb), mercury (Hg), zinc (Zn), and copper (Cu) are considered the most harmful metals for aquatic environments and water quality.

Both P1 and P2 agglomerates leached metals throughout the test. In terms of released concentrations, P2 followed the familiar pattern of higher concentrations in the initial leachings, which decreased with each subsequent leaching. However, P1 departed from this pattern, and released similar concentrations of total soluble metals in the last leaching as in the first. Ni, Pb, Zn and Cu were detected in the agglomerate leachates, and especially Ni levels were high in terms of environmental concern (Figure 8, Table 7).

Total soluble metal concentrations were notably higher in the filter cassettes. This was again the influence of the cement binder, which released not only abundant Ca into the leachates, but also high concentrations of Mg and K.

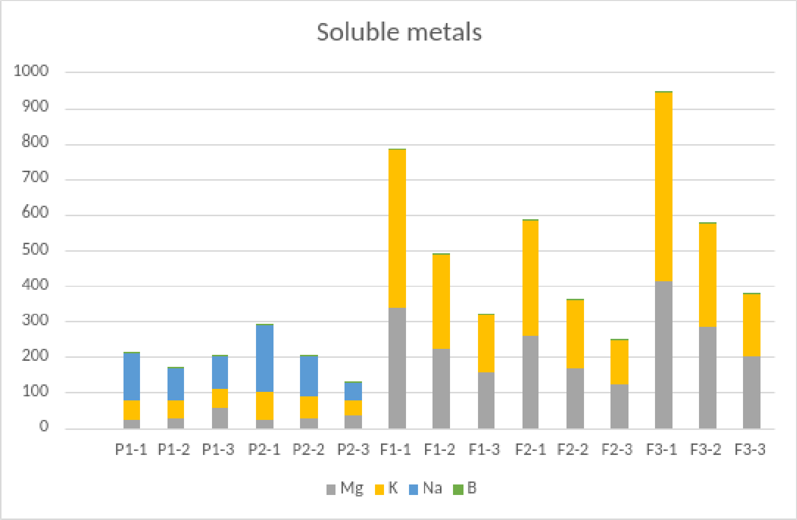


Figure 7. The concentration of most abundant soluble metals (mg/L) in the leachates collected from the different agglomerates (P) and filters (F) at the three different sampling times (-1, -2, -.3). Concentrations of Ca (by far the most abundant metal) have been removed to improve visualisation.

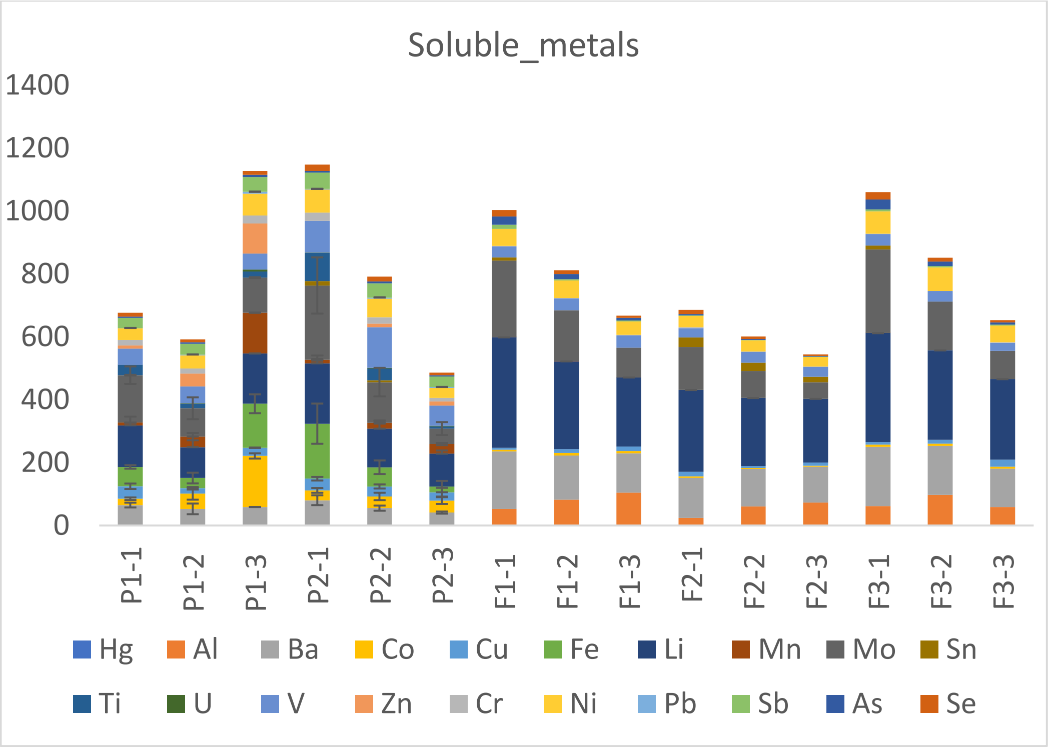
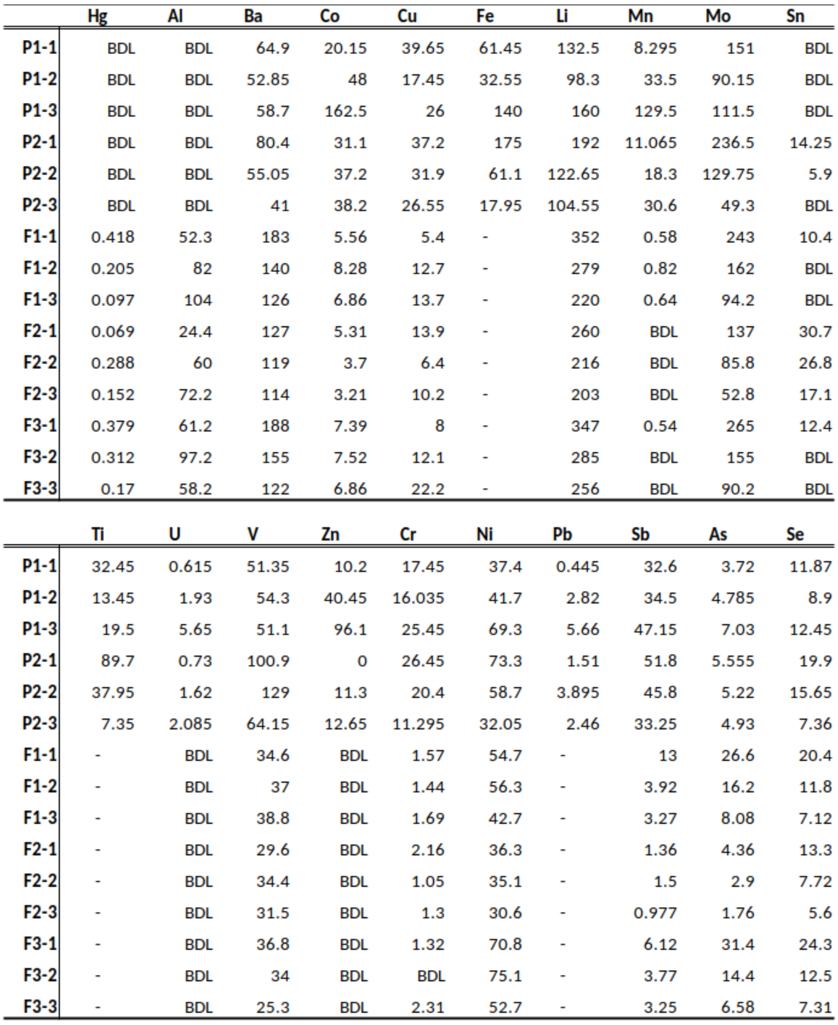


Figure 8. The concentration of soluble metals (µg/L ± SE) in the leachates collected from the different agglomerates (P1, P2, P3) and filters (F1, F2, F3) at the three different sampling times (-1, -2, -.3)

Table 7. Concentrations of soluble metals (ug/L), as presented graphically in Fig. 8



	Hg	Al	Ba	Co	Cu	Fe	Li	Mn	Mo	Sn
P1-1	BDL	BDL	64.9	20.15	39.65	61.45	132.5	8.295	151	BDL
P1-2	BDL	BDL	52.85	48	17.45	32.55	98.3	33.5	90.15	BDL
P1-3	BDL	BDL	58.7	162.5	26	140	160	129.5	111.5	BDL
P2-1	BDL	BDL	80.4	31.1	37.2	175	192	11.065	236.5	14.25
P2-2	BDL	BDL	55.05	37.2	31.9	61.1	122.65	18.3	129.75	5.9
P2-3	BDL	BDL	41	38.2	26.55	17.95	104.55	30.6	49.3	BDL
F1-1	0.418	52.3	183	5.56	5.4	-	352	0.58	243	10.4
F1-2	0.205	82	140	8.28	12.7	-	279	0.82	162	BDL
F1-3	0.097	104	126	6.86	13.7	-	220	0.64	94.2	BDL
F2-1	0.069	24.4	127	5.31	13.9	-	260	BDL	137	30.7
F2-2	0.288	60	119	3.7	6.4	-	216	BDL	85.8	26.8
F2-3	0.152	72.2	114	3.21	10.2	-	203	BDL	52.8	17.1
F3-1	0.379	61.2	188	7.39	8	-	347	0.54	265	12.4
F3-2	0.312	97.2	155	7.52	12.1	-	285	BDL	155	BDL
F3-3	0.17	58.2	122	6.86	22.2	-	256	BDL	90.2	BDL

	Ti	U	V	Zn	Cr	Ni	Pb	Sb	As	Se
P1-1	32.45	0.615	51.35	10.2	17.45	37.4	0.445	32.6	3.72	11.87
P1-2	13.45	1.93	54.3	40.45	16.035	41.7	2.82	34.5	4.785	8.9
P1-3	19.5	5.65	51.1	96.1	25.45	69.3	5.66	47.15	7.03	12.45
P2-1	89.7	0.73	100.9	0	26.45	73.3	1.51	51.8	5.555	19.9
P2-2	37.95	1.62	129	11.3	20.4	58.7	3.895	45.8	5.22	15.65
P2-3	7.35	2.085	64.15	12.65	11.295	32.05	2.46	33.25	4.93	7.36
F1-1	-	BDL	34.6	BDL	1.57	54.7	-	13	26.6	20.4
F1-2	-	BDL	37	BDL	1.44	56.3	-	3.92	16.2	11.8
F1-3	-	BDL	38.8	BDL	1.69	42.7	-	3.27	8.08	7.12
F2-1	-	BDL	29.6	BDL	2.16	36.3	-	1.36	4.36	13.3
F2-2	-	BDL	34.4	BDL	1.05	35.1	-	1.5	2.9	7.72
F2-3	-	BDL	31.5	BDL	1.3	30.6	-	0.977	1.76	5.6
F3-1	-	BDL	36.8	BDL	1.32	70.8	-	6.12	31.4	24.3
F3-2	-	BDL	34	BDL	BDL	75.1	-	3.77	14.4	12.5
F3-3	-	BDL	25.3	BDL	2.31	52.7	-	3.25	6.58	7.31

Conclusions on the UH results

Based on the concentrations of nutrients and heavy metals in the leachates, we recommend using the loose agglomerates instead of the cement matrix filters in any larger scale applications. There was no major difference in the metal and nutrient concentrations between the agglomerate and filter leachates, but the extremely high pH of the filter leachates (>11) could cause problems in larger scale applications. In alkaline conditions, metals tend to precipitate while chemicals such as ammonia become toxic to aquatic life. Additionally, these conditions do not support the development of biofilms and subsequent biological removal of nutrients by the filters, since most microorganisms prefer neutral pH conditions.

Surprisingly, the P2 agglomerates, which had smaller particle size and therefore more overall surface area, seem to leach less soluble metals and nutrients than the larger agglomerates P1. The reasons for this are not known, but based on our observations, agglomerates smaller in diameter than 4 mm could be more suitable for larger scale applications. Though we should also stress that all the tested materials were found to release nutrients and metals on exposure to tap water, and so cannot be expected to absorb or sequester such pollutants from stormwater. Rather, they would act as a source of nutrients and metals, at least until they themselves are depleted. We suggest it would be unwise to deploy any of the tested materials to the field in their current state of development. Further testing at the field lysimeter scale should be undertaken to provide a more complete picture of efficacy and environmental safety of these novel materials.

3.2 Results of leaching tests, TalTech

The results of the series of leaching experiments for R1 (AggP[<4 mm]), R2 (AggP[mix]), and R3 (AggP[>4 mm]) are presented in Tables 8-11 and Figures 9-12. In addition, for the graphically presented results of measurements of the concentration of potassium, sulfate, DOC and TN, the Appendix has been supplemented with a duplication of the data in the form of Table A2.

Dissolved ions

Table 8. Results of measuring the concentration of selected cations in leachate samples.

Parameter, unit	**Tap water**	**Reactor**	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**	**L8**	**L9**
Na^+, mg/L	8.61	**R1**	91.92	40.09	24.93	114.38	52.63	37.63	48.23	36.76	21.23
		R2	40.76	35.67	17.39	73.08	47.02	35.89	57.13	36.46	26.75
		R3	17.27	14.63	12.94	24.69	33.76	26.12	38.23	30.99	26.58
NH_4^+, mg/L	-	**R1**	1.18	0.73	0.41	1.36	0.65	0.41	0.51	0.01	0.06
		R2	0.32	0.46	0.01	0.05	0.12	0.09	0.22	0.01	0.09
		R3	0.19	0.13	0.07	0.40	0.32	0.15	0.59	0.42	0.14
Ca^{2+}, mg/L	62.31	**R1**	613.2	420.0	280.6	1061.7	713.2	640.8	772.9	498.2	566.9
		R2	280.9	292.0	169.1	596.4	487.7	438.4	585.5	498.2	437.6
		R3	127.9	111.7	97.8	164.0	271.9	234.1	375.1	333.9	323.0
Mg^{2+}, mg/L	8.10	**R1**	9.67	9.57	8.16	12.10	7.18	6.94	15.66	15.88	11.00
		R2	9.76	10.28	8.29	9.67	9.99	10.20	13.80	15.88	13.75
		R3	8.75	8.51	8.44	8.64	9.80	9.31	11.38	10.44	11.70

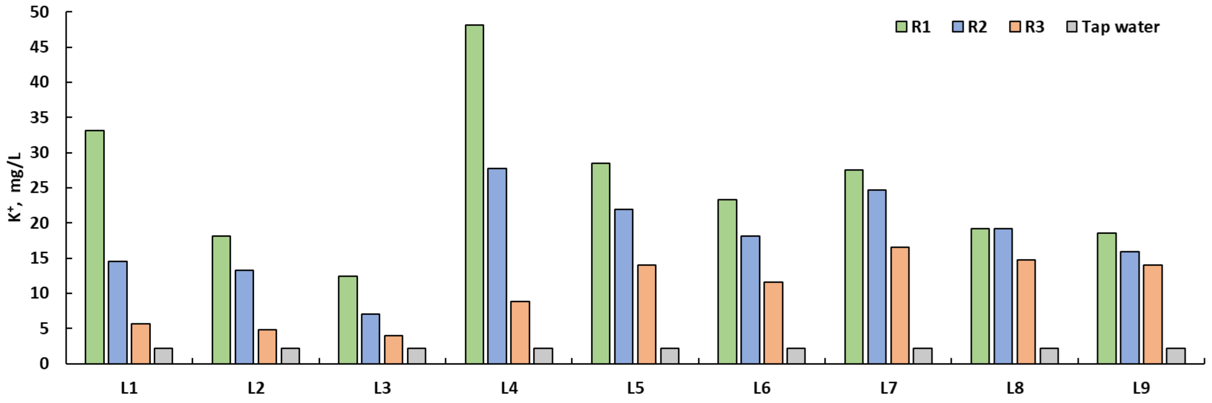


Figure 9. Results of measuring the concentration of potassium cations in leachate samples.

Table 9. Results of measuring the concentration of selected anions in leachate samples.

Parameter, unit	Tap water	**Reactor**	L1	L2	L3	L4	L5	L6	L7	L8	L9
F^-, mg/L	0.13	**R1**	1.34	0.98	0.87	1.70	1.46	1.29	1.07	1.02	0.96
		R2	0.82	0.79	0.69	1.31	1.05	0.96	1.17	0.97	0.91
		R3	0.49	0.43	0.41	1.65	0.86	0.78	0.99	0.89	0.82
Cl^-, mg/L	35.91	**R1**	71.78	45.41	42.87	77.62	47.44	44.29	43.21	39.88	37.78
		R2	51.00	48.29	41.22	65.49	48.95	42.60	52.56	42.78	38.14
		R3	41.36	39.10	38.14	95.01	46.97	43.44	46.56	42.65	41.83
NO_3^-, mg/L	1.03	**R1**	26.45	13.79	10.34	25.89	12.66	-	-	-	-
		R2	15.53	12.90	8.63	24.27	8.06	-	-	-	-
		R3	3.42	2.77	2.10	28.87	6.87	1.26	1.27	1.11	1.23

It should be noted that the concentration of nitrite and phosphate in all leachate samples was below the quantification limit.

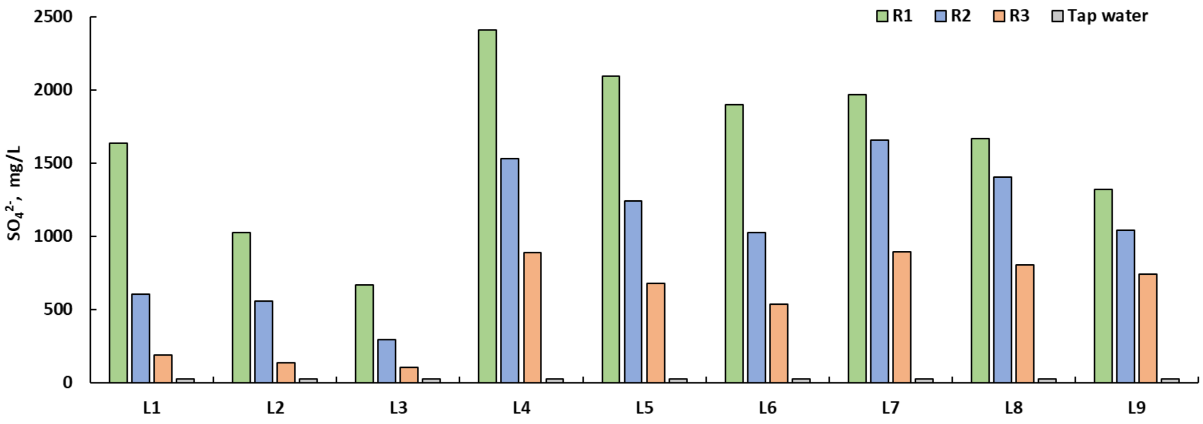


Figure 10. Results of measuring the concentration of sulfate anions in leachate samples.

Regardless of the dissolve ion studied, the concentration in the series L1...L3, L4...L6, and L7...L8 steadily decreased. In turn, the increase in the leaching time led to a certain increase in the concentration of dissolved ions in the leachate: more significant with an increase from 15 min to 24 h (L3 → L4) and less obvious with an increase from 24 to 72 h (L6 → L7). The latter indicates the washing out of cations and anions from the surface of the aggregates with each subsequent leaching. In addition, the particle size was of decisive importance, giving a higher concentration of dissolved ions with the following dependence: R1 (AggP[<4 mm]) > R2 (AggP[mix]) > R3 (AggP[>4 mm]). This observation correlates well with a larger surface area available for leaching in the case of smaller particles.

pH and electroconductivity

Table 10. Results of pH and electroconductivity measurements in leachate samples.

Parameter, unit	Tap water	Reactor	L1	L2	L3	L4	L5	L6	L7	L8	L9
pH	7.42	**R1**	9.19	9.22	9.01	8.93	8.93	9.18	8.53	8.64	8.69
		R2	8.55	8.61	8.45	8.78	8.72	8.63	8.11	8.26	8.31
		R3	8.01	7.94	7.85	8.42	8.30	8.21	8.22	8.19	8.07
EC, µS/cm	416	**R1**	2670	1839	1294	3530	2790	2480	2760	2280	1990
		R2	1400	1310	865	2500	2064	1759	2450	2083	1789
		R3	744	633	578	1682	1366	1183	1676	1478	1390

Nutrients

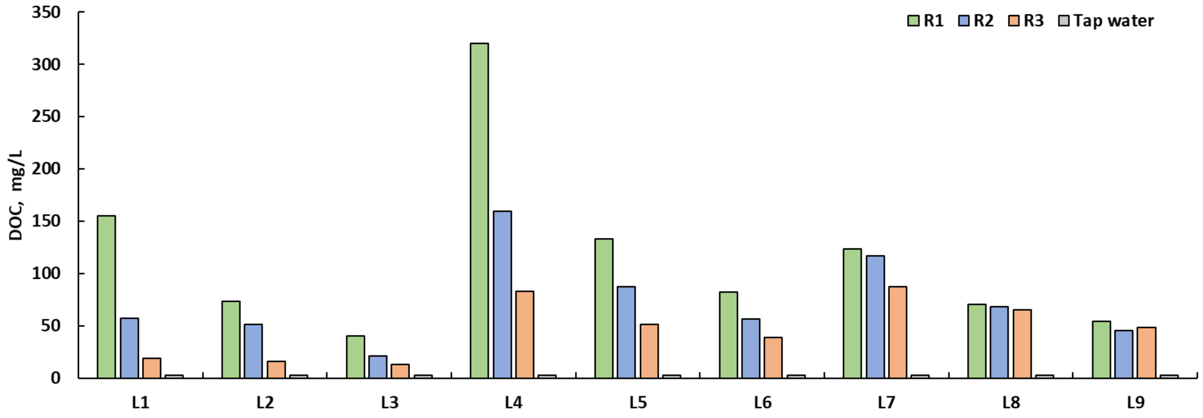


Figure 11. Results of measuring the concentration of dissolved organic carbon (DOC) in leachate samples.

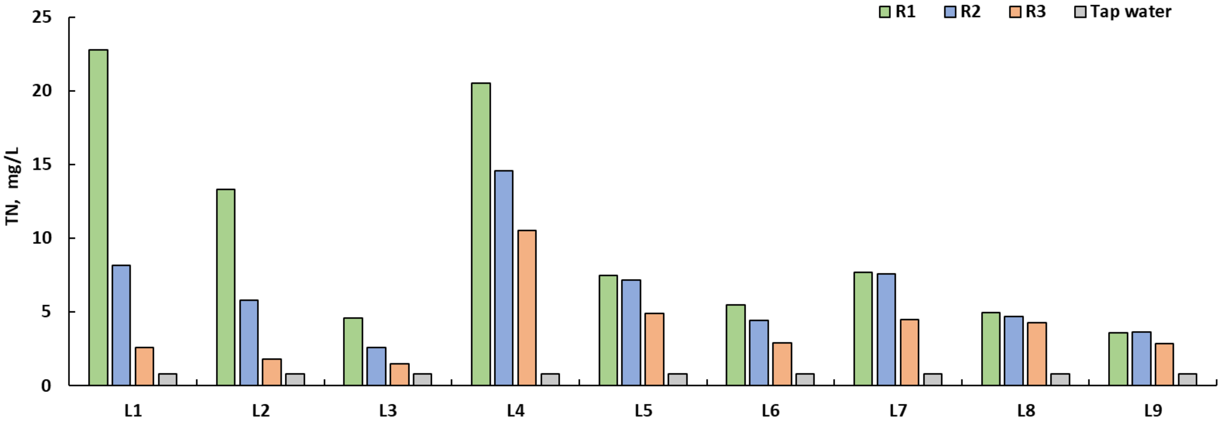


Figure 12. Results of measuring the concentration of total nitrogen (TN) in leachate samples.

Similar to the results obtained for dissolved ions, the pH, conductivity, TN and DOC values were less favorable (higher concentrations within the leaching series) in the case of AggP[<4 mm] (R1) compared to the mixed (R2) and especially large aggregates (AggP[>4 mm], R3). However, it is worth noting the noticeable equalization of the measured TN and DOC concentrations for all the aggregates studied after the last leaching (L9).

Heavy metals

The concentrations of all heavy metals studied (Table 11) in L9 samples were in accordance with the maximum values of pollution indicators established in Estonia (Regulation No. 61, Ministry of Environment, 2019).

Table 11. Results of measuring the concentrations of selected heavy metals in L9 samples.

Parameter, unit	Reactor	L9
As, µg/L	**R1**	4.10
	R2	3.70
	R3	2.90
Cd, µg/L	**R1**	0.030
	R2	0.067
	R3	0.026
Co, µg/L	**R1**	4.10
	R2	7.50
	R3	6.60
Cr, µg/L	**R1**	0.72
	R2	0.71
	R3	0.70
Ni, µg/L	**R1**	9.20
	R2	8.50
	R3	9.80
Pb, µg/L	**R1**	0.19
	R2	0.72
	R3	0.93
Zn µg/L	**R1**	16.0
	R2	68.0
	R3	91.0
Cu, µg/L	**R1**	15.0
	R2	19.0
	R3	9.8
Hg, µg/L	**R1**	<0.015
	R2	<0.015
	R3	0.020

Conclusions on the TalTech results

Regardless of the fraction size of the tested agglomerated (AggP) materials, leaching of nutrients, dissolved organic carbon and ions including heavy metals was detected when these materials were exposed to tap water in nine consecutive leaching experiments (L1…L9). This observation indicates the potential for secondary contamination in case of using the studied aggregates as a filter material for stormwater, at least at the beginning of use. Notably, **the most promising material was found to be AggP[>4 mm]** (R3), with substantially lower leachable concentrations for all measured water parameters.

To obtain a more complete picture of the efficiency and environmental safety of the new aggregated filter materials under study, long-term filtration experiments on synthetic stormwater are currently being carried out in all three reactors (R1, R2, and R3) since January 2025.

3.3 Summary

The results of leaching tests performed by UH and TalTech are summarised in the table below. The results of the third test of the 72-hour exposures are presented for two size fractions of agglomerated material, below 4 mm and larger than 4 mm. The range of detected values summarising both size fractions is presented in the right-hand column.

Table 12. Summary of leaching tests performed in two laboratory setups (UH and TalTech).

Compound	**Unit**	**UH**		**TalTech**		
		0-4 mm	>4 mm	0-4 mm	>4 mm	**Range**
pH		8.7	7.8	8.7	8.1	**7.8 - 8.7**
EC	µS/cm	-	-	1990	1390	**1400-2000**
DOC	mg/L	340	560	54	49	**50 - 560**
N	mg/L	15	26	3.6	2.9	**3 - 26**
P	mg/L	0.4	0.8	-	-	**0.4 – 0.8**
K	mg/L	40	54	18.6	14.0	**14 – 54**
As	µg/L	4.9	7.0	4.1	2.9	**3 – 7**
Hg	µg/L	<DL	<DL	<0.015	0.02	**0.01 – 0.02**
Cr	µg/L	11.3	25.5	0.72	0.70	**0.7 – 26**
Cd	µg/L	<DL	<DL	0.030	0.026	**0.026 – 0.030**
Co	µg/L	38.2	163	4.1	2.9	**3 - 160**
Cu	µg/L	27	26	15	9.8	**10 – 27**
Pb	µg/L	2.5	5.7	0.19	0.93	**0.2 – 5.7**
Ni	µg/L	32	69	9.2	9.8	**9 – 69**
Zn	µg/L	12.7	96	16	91	**13 - 96**

4 Discussion and conclusions

There are no specific, official limit values or guidelines to stormwater quality in Finland. The legislation aimed at the protection of surface waters in Finland (VNa 1022/2006) concerns industries and plants that operate under an environmental permit. These limit values cannot be applied to stormwaters that are generated infrequently and are often uncontrolled.

However, some reference values exist that may be used to assess the ecotoxicological significance of the leaching test results in this report. Most relevant guidelines that could be applied in Finland and other Baltic sea countries were recently examined in a thesis (Sainio 2023). In the thesis, Sainio reviewed stormwater monitoring and reporting practices and proposed a set of guideline values for assessing the impacts of certain contaminants.

The different guideline values may be based on different effect mechanisms. Also the nature and definition of guideline concentration varies depending on, for example, whether total, soluble or bioavailable concentration is measured and whether single samples or long-term averages are concerned. Moreover, the sensitivity of receiving water bodies plays an important role in defining an acceptable concentration.

The guidelines proposed by Sainio (2023) and the guidelines used by city of Gothenburg (2020) are presented in Table 13. In addition, limit values set by the Estonian ministry of environment for wastewater discharges (2019) were examined, but they were not included in the comparison since they are higher than the presented guidelines and cover also other emissions than stormwater.

Table 13. Guideline values used as reference.

Compound	Unit	Proposal by Sainio (2023)	City of Gothenburg (2020)
TOC	mg/l		12
Suspended solids	mg/l		25
pH			6,5-9
Nitrogen	µg/l		1250
Phosphorus	µg/l		50
As	µg/l		16
Hg	µg/l	0,07	0,07
Cr	µg/l	25	7
Cd	µg/l	0,45	0,9
Cu	µg/l	40	10
Pb	µg/l	14	28
Ni	µg/l	34	68
Zn	µg/l	150	30

In this report, the volume of water used in a single leaching test was very small, since the water to agglomerate material -ratio (L/S ratio) was around 1 (0,8-1,5). Thus, the leachate was very concentrated. In comparison, the L/S ratio in the standardized leaching test of waste materials intended to be used in earth construction is 10 (SFS-EN 12457-3).

In general, the levels of nutrients and metals decreased considerably over repeated leachings. The result of the third 72-h leaching of each sample was compared to the presented guideline values. In TalTech samples, metals were only analyzed from the third leaching of the 72h irrigations (L9).

The leachate levels were also dependent on the particle size fraction of filter material, but the relation was not consistent. In TalTech results, the measured values of nutrients and most metals in the coarse fraction (>4 mm) were lower than in the 0-4 mm fraction, whereas it was vice versa in the UH tests.

The measured nitrogen and phosphorus levels were rather high and clearly above the suggested guidelines particularly in the tests performed by UH. This indicates that the agglomerated CDW material has a potential to leach out nutrients particularly in the beginning of its use in the field. The levels of DOC were also much higher than levels usually measured in urban stormwaters. There was a considerable difference in the nitrogen and DOC levels between TalTech and UH, which was probably due to larger dimensions and higher number of repeated leachings per sample applied by TalTech.

Iron, manganese, copper, zinc and nickel were the most abundant metals in the leachates. Cadmium, nickel, lead, mercury, zinc and copper are considered the most harmful metals for aquatic environments and water quality. The levels of Cd, Pb and Hg in this study were below the reference guideline values. The levels of As, Cu, Cr and Zn were mostly comparable or below the guideline values. Ni concentration of >4 mm size fraction exceeded the guideline in UH but not in TalTech results.

In conclusion, the filter material was found to release nutrients and metals on exposure to tap water. The leachate levels decreased considerably in repeated leachings, but the material is likely to act as a source of nutrients at least in the beginning of its application. It is hypothesized that biofilms and subsequent biological removal of nutrients will develop in the filter material when applied in field conditions. It is however not yet known how rapidly such biofiltration will develop or how effective it will be.

Acknowledgements

This activity was supported as part of StoPWa, an Interreg Central Baltic Programme 2021 2027 project co-funded by the European Union.

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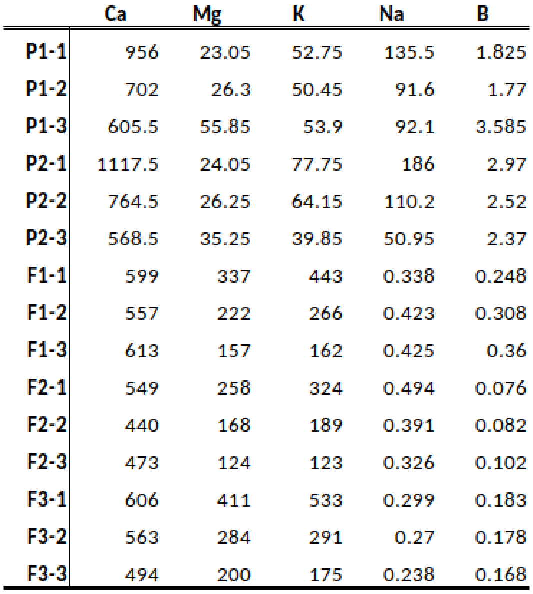
Valtioneuvoston päätös yleisestä viemäristä ja eräiltä teollisuudenaloilta vesiin johdettavien jätevesien sekä teollisuudesta yleiseen viemäriin johdettavien jätevesien käsittelystä. Finlex 365/1994.

Appendices

Table A1. Concentrations of the most abundant soluble metals (mg/L) in UH tests (presented graphically in Fig. 7)



	Ca	Mg	K	Na	B
P1-1	956	23.05	52.75	135.5	1.825
P1-2	702	26.3	50.45	91.6	1.77
P1-3	605.5	55.85	53.9	92.1	3.585
P2-1	1117.5	24.05	77.75	186	2.97
P2-2	764.5	26.25	64.15	110.2	2.52
P2-3	568.5	35.25	39.85	50.95	2.37
F1-1	599	337	443	0.338	0.248
F1-2	557	222	266	0.423	0.308
F1-3	613	157	162	0.425	0.36
F2-1	549	258	324	0.494	0.076
F2-2	440	168	189	0.391	0.082
F2-3	473	124	123	0.326	0.102
F3-1	606	411	533	0.299	0.183
F3-2	563	284	291	0.27	0.178
F3-3	494	200	175	0.238	0.168

Table A2. Concentrations of K^+, SO_4^{2-}, DOC, and TN in leachate samples of TalTech tests.

Parameter, unit	**Tap water**	**Reactor**	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**	**L8**	**L9**
K^+, mg/L	2.2	**R1**	33.1	18.1	12.4	48.2	28.5	23.3	27.5	19.2	18.6
		R2	14.6	13.3	7.1	27.7	21.9	18.1	24.7	19.2	15.9
		R3	5.7	4.8	4.0	8.8	14.0	11.6	16.6	14.8	14.0
SO_4^{2-}, mg/L	24.2	**R1**	1633	1027	667	2409	2092	1896	1967	1664	1318
		R2	602	556	294	1532	1241	1026	1658	1403	1041
		R3	187	137	105	887	678	537	892	801	742
DOC, mg/L	2.7	**R1**	155.2	73.6	40.5	320.4	132.9	82.4	123.6	70.7	53.9
		R2	56.9	51.1	20.9	159.8	87.3	56.5	116.6	68.1	45.6
		R3	18.8	15.7	13.3	82.8	51.1	38.8	87.6	65.3	48.6
TN, mg/L	0.8	**R1**	22.8	13.3	4.6	20.5	7.5	5.5	7.7	5.0	3.6
		R2	8.1	5.8	2.6	14.6	7.1	4.4	7.6	4.7	3.6
		R3	2.6	1.8	1.5	10.6	4.9	2.9	4.5	4.3	2.9