Final Report

Using recycled construction wastes as wetland substrates for pollutant removal in cold climate

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Executive Summary

Constructed wetlands are nature-based decentralized wastewater treatment processes, in which the substrate is an important component, which provides surfaces for biofilm growth and supports the macrophyte. In recent years, recycled aggregates from construction and demolition wastes have shown their great potential as the substrate of wetlands due to their relatively low density, great water absorption, and high porosity. This study investigated the feasibility of using recycling cement wastes from road construction as substrates in the wetlands for wastewater treatment in cold climate by monitoring treatment performance and performing life cycle assessment. Parallel wetland systems with cement and lava rock as respective substrates were operated at 22°C and 5°C for treating Icelandic wastewater, in which several local wild plants and vegetables were planted. The results showed that the wetland system could achieve ~85% and ~51% of organic removals and ~67% and ~34% TN removals at 22°C and 5°C, respectively; and the wetland with recycled cement displayed similar organic and nutrient removals as that with lave stone. Overall, the treated wastewater from the wetland systems fulfilled EU wastewater discharge requirements. Moreover, the heavy metals contents in the cultivated vegetables met WHO standards for human consumption, showing a feasibility of reuse nutrients from the treated wastewater. Finally, an extensive life cycle assessment of conventional septic tank scenario and septic tank + constructed wetland scenario for decentralized wastewater treatment in Iceland was conducted based on experimental and literature data. The use of waste materials as the substate in constructed wetlands benefitted to reduce the overall environmental impact of wetlands. The presence of wetland-based process as posttreatment of septic tank effluent benefited to improve water quality and reduce the eutrophication potential by ~50%, although it resulted in ~14% higher global warming impact. The septic tank + constructed wetland scenario could therefore be especially useful for sensitive areas with eutrophication challenge.

1. Introduction

In Iceland, road construction and wastewater treatment are the two infrastructure sectors in the most need of upgrade. It is widely recognized that the construction industry is a significant contributor to greenhouse gas emissions (GHG). In Iceland, the use of concrete as main building material is particularly problematic due to the high carbon footprint of cement. During the peak of the building boom in 2006 and 2007, a cement plant in Iceland emitted an estimated 150 $ktCO_2$, corresponding to approximately 15% of the total GHG emissions in the road transportation sector in 2019. It is estimated that 0.4-0.5% of all concrete produced is discarded during the construction process; meanwhile, concrete wastes are formed during building demolition. Currently, solid concrete wastes are disposed in landfills or pits in Iceland. Recycling and reusing solid concrete wastes therefore are an important step to achieve more circular economy and making human settlements more sustainable (SDGs No. 9 and 11).

In the wastewater sector, the main challenges are not only bound to the aging collection pipe systems, but also the fact that many communities are not equipped with adequate wastewater treatment facilities, and at worst, are discharging untreated wastes directly to the nearest recipients. Hence, many Icelandic communities cannot well comply to SDG 6 “Ensure availability and sustainable management of water and sanitation for all”. Generally, to meet municipal wastewater discharge standards, biological treatment processes are required following the primary treatment. However, biological secondary treatment faces challenges in cold climate regions. Especially, in Iceland, biological treatment is hindered by both low temperature (mean annual temperature is ~ 6 °C) and low strength nature of wastewater. In addition, Iceland has a very small population with a scattered distribution pattern, especially in rural areas. This creates a challenge to employ conventional biological wastewater treatment facilities in terms of implementation and economic feasibility in Iceland. Therefore, there is a dire need to identify cost-effective and performance-robust technologies to treat wastewater under cold climatic conditions.

As an alternative secondary wastewater treatment, constructed wetlands are considered as a relatively cheap and easy-to-operate nature-based wastewater treatment processes. In the wetlands, natural ecological systems (including wetland vegetation, substrate, and their associated microbial assemblages) are utilized to perform wastewater treatment, which involve aerobic/anoxic/anaerobic biodegradation, sorption, plant uptake, photodegradation (Varma et al., 2021). Compared to free water surface wetlands, sub-surface flow wetlands were advantageous in cold climate because treatment occurs below the ground surface, where bacterial communities are able to be protected from frost action (Ji et al., 2020). For example, in Iceland, a constructed wetland has been built and operated for treating domestic wastewater from the community of Sólheimar in Grímsnes. The preliminary results showed that the wetland achieved better performance in treating septic tank effluent (Pétursson, 2012).

In wetlands, substrate materials perform an important role as they provide binding sites for biofilm development and support aquatic plants (Varma et al., 2021). Generally, natural materials (such as gravels) are widely used as wetland substrate, but they are increasingly in shortage and suffer clogging problems. In recent years, recycled aggregates from construction and demolition wastes have shown their great potential as the substrate of wetlands due to their relatively low density, great water absorption, and high porosity. Several research studies have illustrated that using recycled construction wastes in the wetlands facilitated improving nutrient (such as nitrogen and phosphorus) removals from wastewater matrix due to their greater ammonium/phosphorus adsorption behaviours, as well as sufficient surface area and uneven surface structure for promoting biofilm development. The use of low-cost recycled aggregates in wetlands would benefit for saving natural geological resources, reducing the adverse effects of waste disposal, minimizing carbon footprint of construction materials, and enhancing nutrient removal due to improved adsorption efficiency. Therefore, using construction and demolition waste as biocarriers in constructed wetlands for decentralized wastewater treatment (as illustrated in Figure 1) is a potential solution to reduce greenhouse gas emissions while improving surface water quality through reducing direct discharge of wastewater in Iceland.

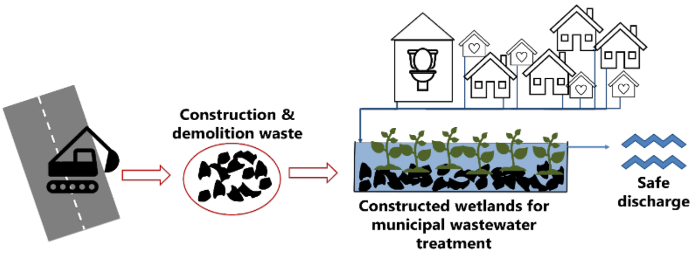

Figure 1. Schematic description of using recycled construction wastes as wetland substrates for pollutant removal.

In Iceland, wetlands cover about 9000 km^2, constituting 19.4 % of the vegetated surfaces of the island, among which 4195 km^2 are drainage wetlands. For centuries, the drainage wetlands were used for grazing by livestock and hay-harvesting. Most of drained wetland use soils as substrate, which facilitates oxidation of organic matter and release of nutrients. On the other hand, Vegagerðin has put great efforts on wetland restoration to minimize disturbance by road construction. Hence, there is great potential of using recycled construction and demolition wastes as wetland substrate during wetland restoration in Iceland. To provide decision-makers with more information, comprehensive research work and economic/environmental benefits are needed before its real application.

This project aims to (1) design and construct recycled cement-based constructed wetland systems in the lab; (2) monitor pollutant removals in the wetlands with different substrates under different operation temperatures; (3) perform economic analysis and life cycle assessment for recycled cement-based constructed wetlands under Icelandic scenario.

2. Performance of Wetland

2.1. Materials and methods

2.1.1. Experimental setup and operation conditions

A lab-scale two-stage sub-surface constructed wetland setup was illustrated in Figure 2. In detail, each tank has a volume of 7 L, 40% of which was packed with the substrate. The primary wastewater (collected from Veitur wastewater treatment plant at Klettagarður, Reykjavík) was delivered to the wetland by a feed pump (Longer, China), and the treated effluent from the first wetland tank freely flew to the second wetland tank via an overflow line. The hydraulic retention time of the two-stage wetland system was ~50 h. A LED lamp (42 W, 6500 K) was located above the wetland and provided light at a cycle of 12 h on/12 h off.

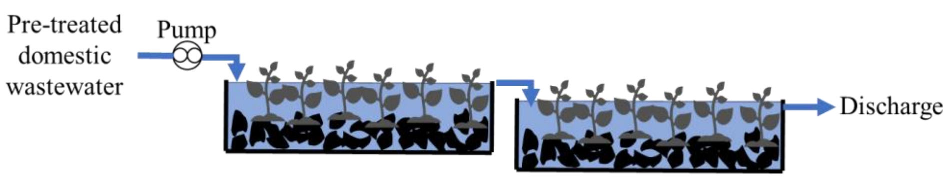

Figure 2. A two-stage sub-surface constructed wetland setup

As shown in Table 1, during Day 0-60, two wetland systems packed with lava stone and cement blocks respectively, were operated in parallel at a temperature of 22°C. In the first wetland tank, *Menyanthes trifoliata* and Icelandic moss that were collected from the Vatnsmýri nature conservation pond were employed as the testing plants. In the second wetland tank, Java Mosi (*Vesicularia dubyana*), *Ceratophyllum demersum*, and Java Fern (*Ceratophyllum demersum*) purchased from local shop (Skrautfiskar) were used as the testing plants. Meanwhile, the basil (*Ocimum basilicum*, Johnson, UK) and lettuce (*Lactuca sativa*, Sluis Garden, The Netherlands) were chosen as the testing vegetables and cultivated in the second wetland tank (for exploring feasibility of nutrient recovery). In detail, several seeds were planted in sponge cubes (2.5 cm × 2.5 cm × 2.5 cm). The sponges containing the seeds were placed in a tray with tap water and a lid (under dark condition). After the seeds germinated (~3 weeks), the sponges with the plants were transferred to the pots (packed with 10-15 clay granules, Jongkind, Netherlands), which were then placed in the second wetland tank. During Day 61-120, one wetland system packed with cement blocks was placed in a freezer (at ~5°C), which was installed with a ventilation system. In both wetland tanks, *Menyanthes trifoliata* and Icelandic moss were used as testing plants.

Table 1. Constructed wetland operation conditions

Time	Substrate	Temp/Light	Plants
Wetland 1 (Day 0-60)	Lava stone	22°C (12 h on - 12 h off)	Stage I: *Menyanthes trifoliata*; Icelandic moss Stage II: Java Mosi (*Vesicularia dubyana*), Ceratophyllum demersum, Java Fern (*Ceratophyllum demersum*), basil (*Ocimum basilicum*), lettuce (*Lactuca sativa*)
Wetland 2 (Day 0-60)	Cement blocks		
Wetland 3 (Day 61-120)	Cement blocks	5°C (12 h on - 12 h off)	Stage I and II: *Menyanthes trifoliata*; Icelandic moss

2.1.2. Water quality analysis

The water quality of feed, effluent from the first tank and from the second tank was analysed weekly. The pH and conductivity were measured using a pH meter (Hach, US) and a conductivity-meter (Hach, US), respectively. The total suspended solids (TSS), chemical oxygen demand (COD), and total nitrogen (TN), Phosphate (PO_4^{3-}) were measured using respective analysis kit (Hach, US) and a spectrophotometer (DR3900, Hach, US), according to the manufacturer's manual. Biological oxygen demand (BOD_5) was measured following standard methods (APHA, 1998). After dismantling of the wetlands, the plant samples were collected and air-dried before heavy metal analysis. Heavy metal contents in the water samples and plant samples were analysed by an inductively coupled plasma-optical emission spectroscopy (ICP-OES, OPTIMA 8300, PerkinElmer, US) and an inductively coupled plasma-mass spectrometry (ICP-MS, iCAP-Q, Thermo Scientific, US), as described in our previous work (Guðjónsdóttir et al., 2022).

To examine the statistical significance of two different sets of data, the *p*-value was calculated based on a two-sample T-test (Microsoft Excel). The statistically significant difference was recorded when *p*-value was <0.05 (a confidence interval of 95%).

2.2 Results and discussion

The water quality profiles are shown in Table 2 and Figure 3. The pH level remained relatively stable at 7.3-8.3 in the three wetlands. However, the conductivity showed high fluctuations in the feed and effluents. This could be attributed to weather and seasonal changes (such as stormwater collection and salt usage on the roads), which affected the wastewater composition. As illustrated in Figure 3, the effluent water quality was comparable in the wetlands with lava stones and cement blocks ($p > 0.05$). The wetland operated at 5°C produced the effluent with significantly higher BOD_5 and TN concentrations than that at 22°C, possibly due to limited plant sorption and biodegradation (Varma et al., 2021). Clearly, the final effluents from the constructed wetlands met Icelandic discharge standards (BOD_5 < 25 mg/L; COD < 125 mg/L; TSS < 35 mg/L) (Reglugerðasafn, 1999), except the TN level in the effluent of the wetland at 5°C for sensitive areas.

In addition, the wetland with cement blocks achieved similar pollutant removal effectiveness as that with lava stones at 22°C, i.e., 85-88% of COD removal; 80-90% of BOD_5 removal; 67-70% of TN removal; 58-63% of PO_4 removal; 94-98% of TSS removal (Table 2). Specifically, the first stage of the wetland system contributed majorly to pollutant removals. In the second stage, COD, TN, PO_4 and TSS were further removed in the wetland systems, while BOD_5 displayed dissimilar removal behaviors in the wetland system under different conditions. It is noted that the composition of municipal wastewater can fluctuate significantly depending in consumption and weather conditions, which is translated in high standard deviations in the feed components (Figure 3). It is therefore important to have a second stage in the constructed wetlands, which can act as a buffer for periods with high organic content in wastewater.

Table 2. Water quality and pollutant removal ratios in the wetlands

	Feed	Lava stones (22°C)		Cement (22°C)		Cement (5°C)	
		Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2
pH	7.4±0.4	7.8±0.2	8.3±0.4	8.0±0.2	8.4±0.7	7.3±0.2	7.5±0.6
Conductivity (µm/cm)	1637± 624	1765± 364	1752± 332	1942± 416	1967± 411	1405± 590	1510± 553
COD removal (%)	-	63±28	88±6	71±20	85±7	44±29	51±31
BOD_5 removal (%)	-	71±16	90±9	80±11	80±24	75±15	65±26
TN removal (%)	-	56±19	70±16	50±19	67±13	32±31	34±32
PO_4 removal (%)	-	32±18	63±15	32±16	48±12	16±14	18±19
TSS removal (%)	-	65±30	98±4	64±32	94±3	73±28	86±12

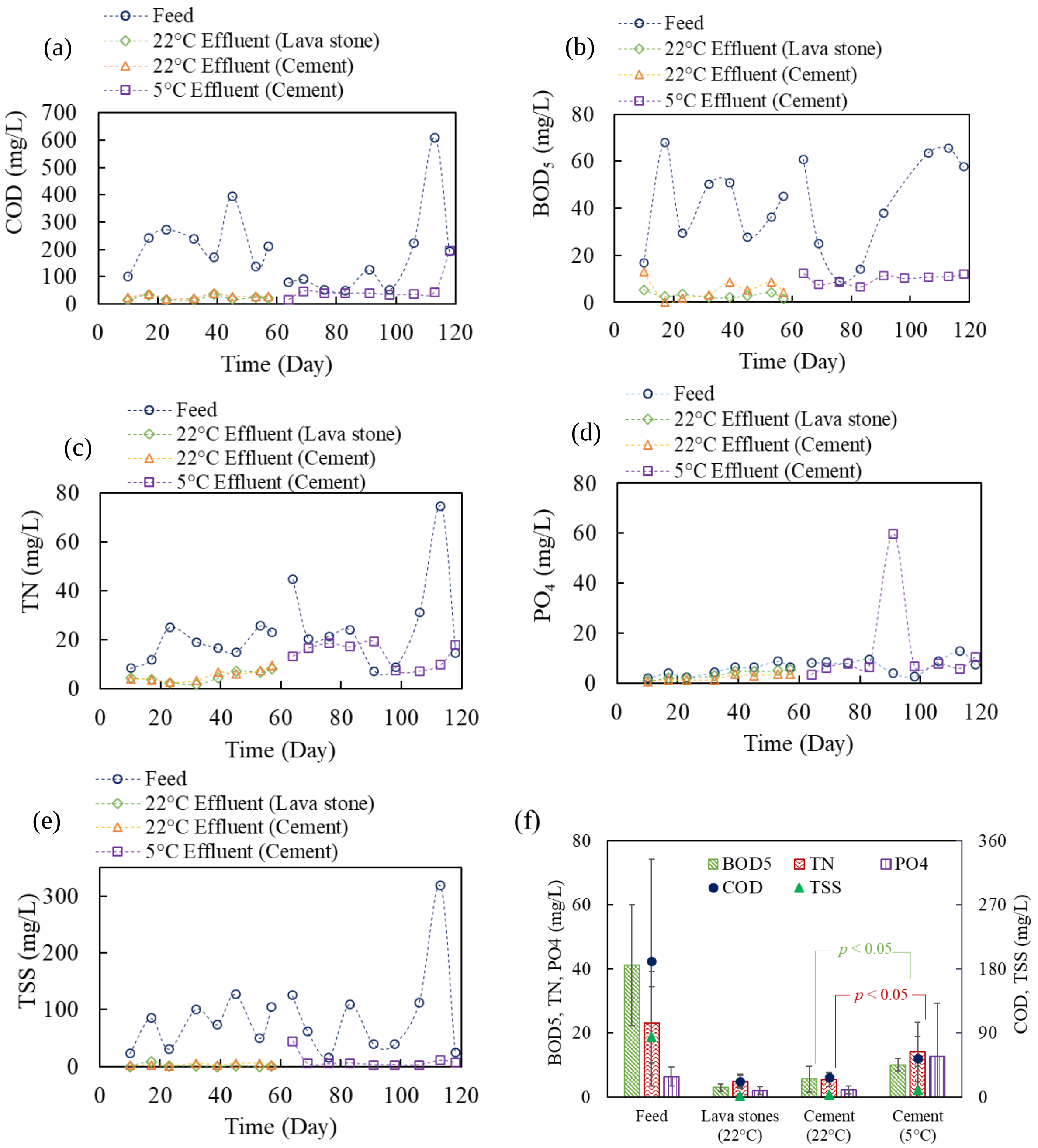

Figure 3. COD (a), BOD_5 (b), TN (c), PO_4 (d), TSS (e), and a summary of water quality parameters (f) in the feed and final effluents of the wetland systems.

The heavy metal contents in the feed and effluent of the wetland system operated at 22°C were described in Table 3. It was observed that a higher levels of Ca, Si, Sr, and Ti occurred in the effluent of the wetland with cement, due to their leaching from the cement blocks. The effluent in the wetland with lava rock presented higher Cu, Mn, Mo, and Zn levels, which could be attributed to their leaching from the lava rock (Arnórsson & Oskarsson, 2007). At 5°C, lower heavy metal contents in the final effluent compared to the feed, which may be attributed by the limited leaching of heavy metals from the substrate and effective sorption/plant uptake of heavy metals.

Table 3. Heavy metal and metalloid concentration in feed and final effluents

mg/L	Feed (22°C)	Final effluent (22°C)		Feed (5°C)	Final effluent (5°C)
		Lava stone	Cement		Cement
Al	0.0388±0.0363	0.0353±0.0259	0.0208±0.01863	10.2022±7.9070	2.8755±0.6641
As	<0.001	<0.001	<0.001	0.0024±0.0006	0.0013±0.0008
Ba	0.0054±0.002	0.0092±0.0021	0.0097±0.0014	0.0597±0.0334	0.0277±0.0176
Ca	21.2067±1.3719	20.0533±0.9724	30.0200±1.1690	31.6223±10.1176	28.2199±9.1061
Cd	<0.001	<0.001	<0.001	0.0007±0.0004	0.0001±0.0000
Co	<0.001	<0.001	<0.001	0.0075±0.0056	0.0021±0.0004
Cr	<0.001	<0.001	<0.001	0.0193±0.0518	0.0023±0.0010
Cu	<0.001	0.0064±0.0004	<0.001	0.0597±0.0638	0.0148±0.0025
Fe	<0.001	<0.001	<0.001	11.9093±12.2394	3.3562±1.2311
K	11.0700±2.4575	8.6167±1.5234	10.0600±2.1047	17.9983±3.6561	16.1694±10.1316
Mg	19.9700±4.5317	18.4600±2.5803	19.8800±4.6796	36.8318±17.4055	37.6747±20.4462
Mn	0.0155±0.0177	0.0186±0.01207	0.0078±0.0090	0.2783±0.1907	0.1444±0.612
Mo	0.0014±0.0005	0.0047±0.0022	0.0020±0.0004	0.3592±0.5000	0.0085±0.0065
Na	>500	>500	>500	227.4228±154.2035	236.4680±144.6938
Ni	0.0105±0.0093	0.0054±0.0023	0.0039±0.0055	0.0251±0.0199	0.0061±0.0009
Pb	<0.001	<0.001	<0.001	0.0210±0.0143	0.0035±0.0014
Sb	<0.001	<0.001	<0.001	0.0028±0.0034	0.0005±0.0002
Se	<0.001	<0.001	<0.001	-	-
Si	19.8667±3.4195	6.8533±5.5697	9.9800±2.6535	17.7945±6.2217	10.0160±3.3953
Sn	<0.001	<0.001	<0.001	0.0007±0.0003	0.0005±0.0002
Sr	0.1139±0.0213	0.1112±0.01063	0.2020±0.0209	0.2633±0.1144	0.2612±0.1388
Ti	0.0415±0.0034	0.0411±0.0015	0.0596±0.0024	0.0763±0.0824	0.0367±0.0342
V	0.0038±0.001	0.0028±0.0004	0.0022±0.0002	0.1123±0.1036	0.0069±0.0011
Zn	0.0221±0.0061	0.0464±0.0427	0.0172±0.0121	1.3570±1.1459	0.1374±0.0369
Hg	<0.001	<0.001	<0.001	0.0001±0.0001	0.0003±0.0001

Figure 4 shows the status of plants in the wetlands at different operation times. It was observed that at 22°C, the testing plants grew with extending operation time; while at 5°C, the testing plants appeared to stop growing and their leaves dried out. At the end of operation of the wetlands with lava stone and cement (22°C), the lettuce and basil were collected, and their growth parameters (leave number, leave length, and maximum plant (except root) length) were measured and shown in Table 4. The lettuce plants in the lava stone and cement wetlands grew to a similar height at ~18 cm, however, significant differences were found in the leave number and max leave length (p<0.05). The lettuce plants from the lava stone wetlands developed better, with ~ 2 more leaves per plant and larger leaves. The basil plants showed an opposite pattern, where the only significant difference of the plant height between lava stone- and cement-based wetlands was noticed, i.e., the plants in the cement-based wetland with being ~1.6 cm higher. It is noted that the organic/nutrient levels in the two wetlands were relatively similar, so these differences might result from the dissimilar availabilities of micronutrients (such as Zn, Mo, Cu, Mo, leaching from the substrate) for the plants.

Table 4. The growth parameters of plants in the wetlands (22°C)

		Lava stone	Cement	*p*-value
Lettuce (collected on Day 42)	Leave number	9.3±1.7	7.3±1.3	0.02
	Max. leave length (cm)	12.9±2.4	10.1±0.8	0.01
	Total height (cm)	17.9±3.3	17.6±3.2	0.87
Basil (collected on Day 58)	Leave number	9.8±2.8	9.7±2.9	0.84
	Max. leave length (cm)	2.4±0.6	2.6±0.6	0.14
	Total height (cm)	3.6±1.6	5.3±2.3	0.00

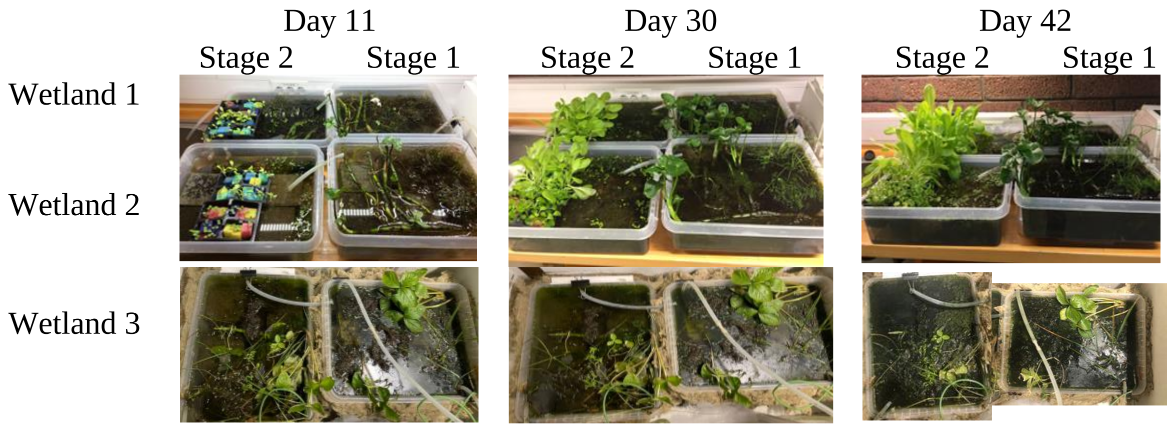

Figure 4. Photos of the wetlands at different operation times.

Meanwhile, the *Menyanthes trifoliata*, basil, and lettuce plants collected from wetlands 1 and 2 were dried and the heavy metal contents in the dried plants were analyzed, as shown in Table 5. The metal contents in the three types of plants met WHO standards for human consumption (World Health Organization, 2006), which showed a potential for nutrient recycling. Specifically, the basil plants contained higher levels of Al, Co, Ni, Se and Zn elements, while the lettuce plants contained more Mn in the lava rock-based wetland compared to those in the cement-based wetland. Meanwhile, *Menyanthes trifoliata* in the lava rock-based wetland contained more As, while that in the cement-based wetland contained more higher Ba, Co and Se. This was possibly related to the different contents of these elements in both wetlands (Table 3) and dissimilar nutrient uptake behaviors of different plants.

Table 5. Heavy metal and metalloid contents (mg/g dry weight) in dried plant samples.

mg/g	WHO guideline	Cement			Lava stone		
		Menyanthes trifoliata	Basil	Lettuce	*Menyanthes trifoliata*	Basil	Lettuce
Al	-	0.1581±0.0154	0.0395±0.0013	0.0332±0.0007	0.0865±0.0490	0.0898±0.0000	0.0298±0.0032
As	0.008	0.0003	<0.0003	<0.0003	0.0027±0.0000	<0.0004	<0.0002
Ba	0.302	0.0066±0.0008	0.0049±0.0005	0.0050±0.0007	0.0033±0.0002	0.0050±0.0004	0.0049±0.0009
Ca	-	4.9790±0.0279	9.6630±0.3897	14.4414±0.3558	4.6689±0.1718	10.3228±0.0192	13.1959±0.8500
Cd	0.004	<0.0003	<0.0003	<0.0003	<0.0003	<0.0004	0.0003±0.0000
Co	-	0.0031±0.0010	0.0014±0.0001	0.0003	0.0018±0.0004	0.0047±0.0001	0.0005±0.0002
Cr	-	0.0007±0.0001	0.0004±0.0000	0.0005	0.0005±0.0000	0.0009±0.0003	0.0008±0.0001
Cu	-	0.0209±0.0023	0.0148±0.0013	0.0115±0.0011	0.0194±0.0006	0.0212±0.0025	0.0140±0.0017
Fe	-	1.3307±0.1328	0.0760±0.0009	0.0818±0.0057	0.8739±0.1799	0.0626±0.0073	0.0784±0.0081
K	-	26.1725±3.0755	41.8221±2.3736	45.0533±1.4805	25.9388±3.0051	40.6733±0.5670	55.0729±4.8438
Mg	-	3.9166±0.3054	7.1420±0.4602	4.0176±0.3371	5.3547±1.0082	9.5481±0.2207	4.8554±0.3183
Mn	-	0.3887±0.1044	0.0803±0.0089	0.0567±0.0022	0.2247±0.0022	0.1685±0.0021	0.1023±0.0258
Mo	0.0006	0.0006±0.0000	0.0004±0.0001	0.0003	0.0004±0.0000	0.0005	0.0004±0.0001
Na	-	7.9827±1.9583	1.9518±0.2525	10.5041±1.2934	9.3918±2.0592	1.5547±0.2086	11.9966±3.4579
Ni	0.107	0.0072±0.0033	0.0037±0.0003	0.0011±0.0004	0.0026±0.0001	0.0094±0.0003	0.0012±0.0002
Pb	0.084	0.0004	0.0003	0.0003	0.0003	<0.0004	<0.0002
Sb	-	<0.0003	<0.0003	<0.0003	<0.0003	<0.0004	<0.0002
Se	0.006	0.0022±0.0005	0.0016±0.0002	0.0026±0.0005	0.0010±0.0001	0.0037±0.0002	0.0026±0.0003
Si	-	0.6180±0.0470	0.1861±0.1861	0.3753±0.0292	0.6779±0.0093	0.0000±0.0000	0.2895±0.0097
Sn	-	0.0005±0.0000	0.0004	0.0003	0.0004	0.0005	0.0004
Sr	-	0.0411±0.0008	0.0661±0.0048	0.0873±0.0026	0.0374±0.0023	0.0558±0.0019	0.0652±0.0134
Ti	-	0.0197±0.0021	0.0193±0.0005	0.0261±0.0009	0.0172±0.0068	0.0188±0.0003	0.0249±0.0026
V	0.047	0.0016±0.0002	<0.0003	0.0003±0.0000	0.0008	0.0004	0.0003
Zn	-	0.0855±0.0022	0.0510±0.0067	0.0600±0.0007	0.0847±0.0042	0.1064±0.0060	0.0960±0.0075
Hg	0.007	<0.0003	<0.0003	<0.0003	<0.0003	<0.0004	<0.0002

3. Life Cycle Assessment

The DIN standards (ISO 14040, 2006; ISO 14044, 2006) were followed for this LCA.

3.1. Goal definition

The overarching goal of this LCA was to evaluate the environmental impacts of constructed wetlands as second-stage after septic tank treatment for wastewater treatment in Iceland, compared to conventional septic tank treatment alone. A superior effluent quality generally causes higher energy consumption (Hauschild, 2015), therefore it is important to carefully evaluate how environmental impacts are reduced by the superior effluent quality or increased by higher construction and treatment efforts when the constructed wetland was applied.

3.1.1. Method, assumption and impact limitations

Two different scenarios were analysed and compared in this project:

- Scenario 1: Septic tank (generally used decentralized wastewater treatment process in Iceland)
- Scenario 2: Septic tank + 2 stage constructed wetland (proposed process in this study)

Scenario 1 represents a currently common situation in rural Iceland, while scenario 2 describes a possibility for improved wastewater treatment. The available experimental data from our current studies performed in the environmental engineering lab of the University of Iceland were used, else data were carefully selected from literature.

However, the data availability is very limited, therefore the LCA relies considerately on assumptions (see 4.7).

Three impact categories were recommended for wastewater treatment LCA to represent the energy- and toxicity-related emissions into air and water (Hauschild, 2015):

- Climate change
- Eutrophication
- Ecotoxicity

Based on the impact factors for each impact category from the ecoinvent database (Wernet, 2016), it was assumed that the positive impacts by the improved effluent quality would be represented in the marine eutrophication and ecotoxicity categories, while the increased construction and treatment activity would be represented in the climate change category (Hauschild, 2015). It is noted that micropollutant data was not available in this study, so that ecotoxicity was not investigated, while climate change and eutrophication categories were considered for a comparison of both scenarios.

3.1.2. Decision level

A more detailed LCA comparing different wastewater treatment scenarios would be considered as: Situation B, macro-level decision support: “Forecasting and analysis of the environmental impact of pervasive technologies” (Hauschild, 2015).

3.2. Scope definition

3.2.1. Deliverables

This LCA project aims to compare existing wastewater treatment in rural Iceland (septic tanks) with an improved treatment scenario (septic tanks + constructed wetlands). In addition, the advantages and disadvantages of applying a wetland treatment as a posttreatment are evaluated.

3.2.2. Function

The function of this LCA is to treat wastewater to ensure safe discharge and protection of water bodies. The Icelandic scenario is used to conduct this LCA, and the sample population is 10. This study is dealing with a monofunctional system.

3.2.3. Functional unit

The functional unit of this LCA is 1 m^3 of treated wastewater. The lifespan of septic tanks and constructed wetlands is considered as 20 years (Flores et al., 2019; Garfí et al., 2017; Hashemi & Boudaghpour, 2020; Resende et al., 2019).

3.2.4. System boundaries and cut-offs

The system components considered in this LCA were shown in Figure 5 (a) for scenario 1 and (b) for scenario 2. The end-of-life phases for the treatment facilities were not considered, as it was reported that those emissions were negligible compared to the overall system emissions (Corominas et al., 2020; Garfí et al., 2017).

Transport of construction material was not included in this study, as it was reported to be negligible compared to overall impacts (Flores et al., 2019; Garfí et al., 2017). Moreover, the focus of this LCA lied in showing the differences between septic tank alone and septic tank followed by constructed wetland treatment. The transportation during construction phase for constructed wetlands was not expected to be relevant and the only transportation required during operation was for the septic tank sludge, which was identical in the two scenarios.

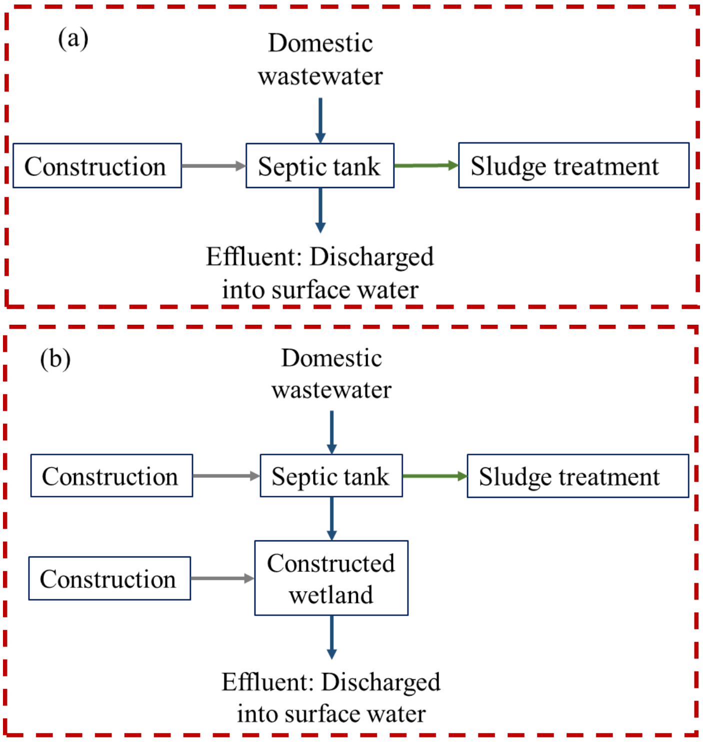

Figure 5. System boundaries and cut-offs

3.3. Representativeness of data and regional aspect

It is noted that the results will only be representative for Icelandic conditions because of the collected data and climate assumptions. When pre-made processes from the openLCA database were used, the

European or "Rest of the World" ones were chosen, depending on availability, and adapted as explained in 4.7. Moreover, biological processes in septic tanks and constructed wetlands are highly dependent on temperature. If Icelandic data was not available, the literature data collected in similar climates were adopted.

Technological and temporal representativeness were ensured by choosing real or realistic scenarios. Septic tanks are commonly applied in rural areas worldwide. When primary data was unavailable, data such as gaseous emission and removal efficiencies were taken from literatures. Maintenance, such as septic tank sludge disposal, was also considered under the Icelandic scenario. It was expected that wastewater content and volume could change throughout the accounted study period of 20 years (life span of infrastructure) considering population growth, tourism and changing water consumption patterns. Moreover, climate change could change temperatures and thus influence removal values in the treatment systems within their lifespan. These factors could slightly influence the LCA results.

3.4. Basis for impact assessment

The impact assessment method TRACI was used instead of the commonly used ReCiPe method, because TRACI also includes COD and BOD_5 parameters (the data are available from our lab experiments) in eutrophication potential evaluation (Corominas et al., 2020). The data related to flows and processes were taken from the ecoinvent database (Wernet, 2016).

3.5. Requirement for comparative studies

Requirements for comparative studies set in the ISO standard (ISO 14044, 2006) are considered. This includes identical functional units and corresponding methodological considerations. The latter consist of treatment performance, system boundaries, data quality, input and output evaluation and impact assessment.

3.6. Critical review needs

A critical review is required when a LCA is used in a decision-making context. The present LCA was a feasibility assessment and will not directly be used for decision-making.

3.7. Life cycle inventory analysis

3.7.1. Data overview

The available experimental data from our current studies were used, including the pollutant removal efficiencies in the constructed wetlands and the untreated wastewater quality data. When literature data were needed, the data collected in similar climates were carefully selected to represent the Icelandic scenario. However, literature data were not site-specific. The impact of the individual process was calculated in the openLCA software and then further processed with Microsoft Excel.

3.7.2. Documentation of system modelling per life cycle stage

The wastewater treatment processes were split into two life cycle stages: construction and treatment. These two stages were analysed for the septic tank and constructed wetland. The sludge in Iceland is conventionally landfilled in a municipal landfill, without methane collection. The openLCA process "*treatment of municipal solid waste, sanitary landfill*" was used for sludge treatment, which included a construction process for the landfill site. It was adapted to Iceland as explained in Table 6. The construction inventories for the septic tank and constructed wetland were simplified due to the lack of reliable data. Only the major components were considered in order to avoid uncertainty, as smaller construction components are expected to contribute negligibly to the overall impact.

Table 6. Life cycle inventory analysis for construction & operation phase

Construction of septic tank	Details
Volume= PE×200 L+2000 L = 4 m^3	(Umhverfisstofnun, 2022) openLCA process for Europe: *excavation, hydraulic digger*
Wastewater flow per capita = 200 L/d	(Umhverfisstofnun, 2022)
Fiberglass: m = 125.2 kg	31.3 kg/m^3 tank volume (Survival Tech Shop, 2023)
Pipes: 50 m×4.06 kg/m= 203 kg	5” PVC pipes (~12.7 cm) with 4.06 kg/m (PVC Pipe Supplies, 2023). The length of piping system is highly dependent on the specific case. The present scenario includes 10 PE, so ~2 households connected to the same wastewater treatment system. A conservative estimation of a total of 50 m of piping was taken for the septic tank scenario and 20 m of piping for the constructed wetlands. openLCA process: *polyvinylchloride production, suspension – RoW polymerization* (Resende et al., 2019)
Construction of wetland	
Volume= 6.95 m^3	Volume=HRT×Q/0.6 = 50 h×2 m^3/d/0.6 (considering 40% biocarrier packing ratio) Data from laboratory experiments openLCA process for Europe: *excavation, hydraulic digger*
Biocarrier: Recycled concrete gravel mass= 4.61 t	mass=0.4×6.95m^3×1.66 t/m^3 Data from laboratory experiments openLCA process: *waste concrete gravel* | *market for waste concrete gravel* (global)
Pipes: 20 m	See pipes for septic tank
Plants	Plants do not have a positive or negative impact, as they are relocated from somewhere else and continue growing in the wetlands.
Liner: 1.62 kg Polyethylene	Wetland height: 0.4 m and Volume: 6.95 m^3, leading to length=width = 4.17m A_{liner} = Area + 4×length×height = 17.4m^2+4×0.4m×4.17m = 24.04 m^2 Liner thickness = 7mm V = 24.04m^2×0.007m = 0.017 m^3 m = 0.017m^3×95kg/m^3= 1.62 kg openLCA process for Europe: *polyethylene, low density, granulate*
Operation of septic Tank	
Septic tank effluent COD: 73.17 mg/L BOD_5: 30.72 mg/L TN: 21.92 mg/L PO_4: 6.10 mg/L	The effluent data were calculated based on the typical septic tank removal ratios in the references (EPA, 2002; Umhverfisstofnun, 2022) and the feed wastewater parameters measured in the laboratory.
Gaseous emissions per m^3 wastewater: N_2O: 0.03 g/m^3 CH_4: 55 g/m^3	CO_2 emissions from wastewater are not considered because of their biogenic origin and should not be included in the total emissions (Eggleston et al., 2006; Leverenz et al., 2010)
Sludge production 1.91 kg/m^3	Based on total sludge accumulation per capita for emptying every 2 years (Mahon et al., 2022)

Sludge treatment	A separate process was conducted for septic tank sludge treatment. The process *treatment of municipal solid waste, sanitary landfill* from the ecoinvent database was adapted by changing electricity requirements to the Icelandic scenario and replacing tap water heating requirements to geothermal heating scenario.
Operation of wetland	
Effluent COD: 35.85 mg/L BOD_5: 10.75 mg/L TN: 14.46 mg/L PO_4: 0.85 mg/L	Calculated based on the septic tank effluent and removal ratios from the lab experiment
Gaseous emissions CH_4: 0.64 g/m^3 N_2O: 0.02 g/m^3	Similar climate and structural conditions were chosen based on the reference (i.e., Koo wetland Estonia) (Søvik et al., 2006). It is known that there are less CO_2 and CH_4 emissions in colder temperatures (Maucieri et al., 2017; Teiter & Mander, 2005). CO_2 emissions from wastewater were not considered because of their biogenic origin and will not be included in the total emissions (Eggleston et al., 2006)

3.8. Results and discussion

The calculated emissions in global warming and eutrophication categories from construction, operation and sludge treatment phase are shown in Figure 6. The contribution ratios of individual items to global warming and eutrophication impacts were calculated and plotted in Figure 7.

The construction phases represented less than 3% of the total impact in global warming category and less than 1% in eutrophication category. This was contrary to the findings in a previous study, where construction of non-intensive wastewater treatment technologies contributed majorly (Corominas et al., 2020). This difference could be attributed to the simple setup of septic tank and wetland, without requiring any electrical parts such as pumps and exclusion of transportation. In detail, the main contributor to global warming potential in both scenarios was the glass fiber tank production (>50%), closely followed by pipe production, while the remaining excavation and liner production contributed negligibly (<5%). Specifically, during the construction of the wetland alone, the pipe production was largely dominant, while the use of waste cement gravel as substrate led to a negative contribution ratio to global warming (-48%) (Figure 7a). In the combined scenario, this negative contribution improved and was present at -5%.

During operation, the sludge treatment contributes significantly to the global warming impact (~50%) in both scenarios. This could be largely attributed to methane emissions (Figure 7b), as conventional landfills in Iceland do not collect methane for reuse. This impact could potentially be reduced to zero in the global warming category by implementing the methane collection and reuse process, as the reuse of methane can be accounted as negative emissions, balancing out the other emissions. Another improvement of sludge treatment could be its reuse in agriculture, where it could replace conventional fertilizer and therefore avoid emissions from fertilizer production (Polruang et al., 2018; World Health Organization, 2006). Other constructed wetland studies showed a higher global warming impact mostly due to pumping and aeration (Resende et al., 2019). The present scenario was however completely gravity-driven and without implementing additional aeration, which was favorable for decentralized application because of the systems simplicity (Garcia et al., 2020; Hijosa-Valsero et al., 2010). Nevertheless, the advanced treatment scenario (septic tank + constructed wetland) only resulted in ~14% higher global warming impact.

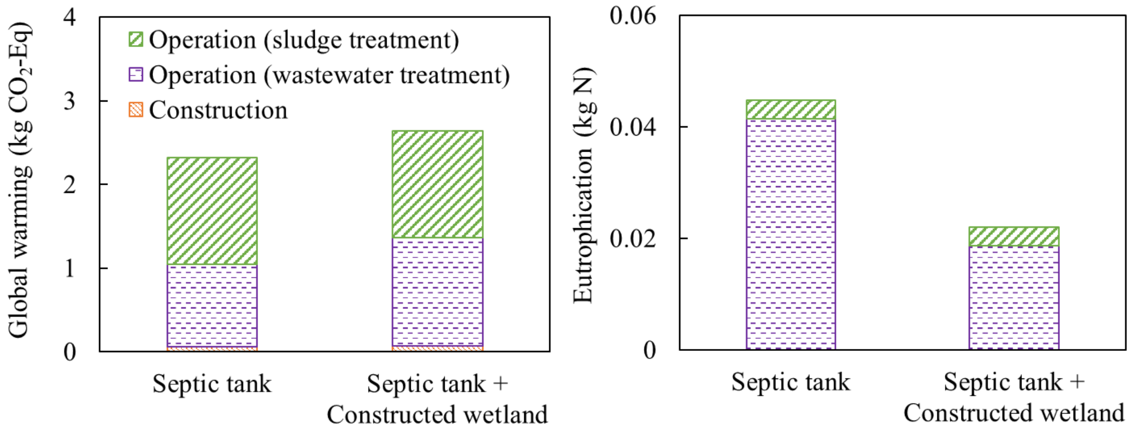

Figure 6. LCA impact in global warming (a) and eutrophication (b) categories

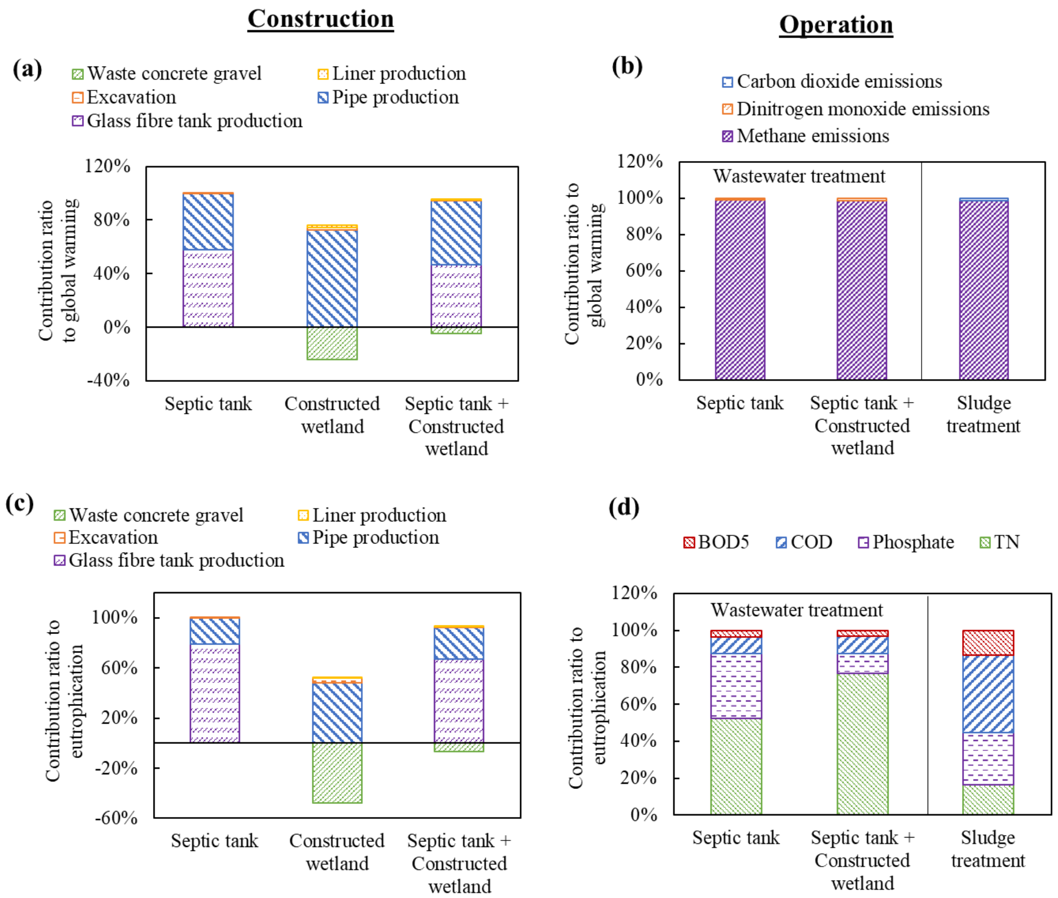

Figure 7. Contribution ratio of each item to global warming (a & b) and eutrophication (c & d) categories

Regarding Eutrophication potential, the main emission driver was also the glass fiber tank production (<75%), followed by pipe production (~20%) for both septic tank alone and the combined system in the construction category. The positive emission contribution of pipe production during construction of the constructed wetland could almost be traded-off by the negative emissions of using recycled cement (Figure 7c). The main potential to reduce the construction environmental impact therefore lies in the septic tank material choice. On the other hand, the septic tank + wetland system resulted in a significantly lower eutrophication potential (~50%) than the septic tank alone, which was attributed by further reduction of organic and inorganic components in the constructed wetland. TN contents represented the major contributor in the eutrophication category (Figure 7d), which was in accordance with the findings in the previous studies (Resende et al., 2019; Roux et al., 2010). The removal of TN in decentralized wastewater treatment systems should therefore be further investigated in future research to efficiently reduce eutrophication potential. Last, the sludge treatment eutrophication impact distribution (Figure 7d) may be different from the real situation, as this is based on a municipal waste landfilling process with only 22% compostable material (Wernet, 2016) and the landfill construction (treating a combination of municipal wastes and sludge) was included in the operation category in this case. These emissions depend highly on landfill technology such as leachate treatment or heat recycling (Sauve & Van Acker, 2020).

Overall, the results showed an advantage of two-stage treatment regarding eutrophication potential, although its global warming potential is slightly higher. This indicated that it could be employed in sensitive areas, with eutrophication risk. However, the main driver in the global warming category is the sludge treatment type and lack of methane reuse at the landfilling site, which should be tackled potentially by updating methane collection/reuse system to limit its emissions. These solutions are manifold (agricultural reuse, electricity production, thermal reuse, conversion to biodiesel or methanol etc.) and the relevant technologies have been well developed (Polruang et al., 2018; Sauve & Van Acker, 2020).

4. Cost Analysis

41. Inventory

For simplification and comparison purposes, only primary materials were considered for the capital costs, while construction, labor, and transport costs were excluded as they highly depend on the situation of the construction sites. The calculations rely on the same assumptions as those in the LCA (Section 3): septic tank and constructed wetland systems are sized for 10 people equivalent with an HRT of ~50 h; the constructed wetland is operated in two-stage; biocarriers are the cement from construction waste.

Table 7. A summary of capital and operational cost estimation

Capital costs	Details
Septic tank: 337.43 €	90 $/m^3$; For 4 m^3 (Alibaba, 2023b)
Septic tank piping: 171.24 €	0.9 $/kg; For 50 m (Alibaba, 2023c)
Constructed wetland piping: 68.50 €	0.9 $/kg; For 20 m (Alibaba, 2023c)
Liner: 2.51 €	1.66 $/kg; For 24.04 m^2 (Alibaba, 2023a)
Biocarriers: Recycled concrete	Waste product free of charge
Operational costs	
Septic tank emptying: 75.31 €/year	Emptied every 3 years, payment distributed over this timespan (Hrunamannahreppur, 2023)

4.2. Results and discussion

Table 8 shows the individual and total costs for each item in both scenarios. The total costs between the two scenarios were almost comparable (0.14 €/m^3), which could be attributed to the extremely low capital and operation costs of the constructed wetlands. Nevertheless, the cost for septic tank + constructed wetland was lower than that of gravity-driven membrane filtration systems in our previous studies (Hube et al., 2023; Shami & Wu, 2021).

In detail, the main component was the sludge treatment at 0.1 €/m^3, which was based on the price charged by municipalities for houseowners (Hrunamannahreppur, 2023). As sludge treatment cost was independent of flow, such cost would decrease with increasing wastewater production. In addition, the material costs were relatively low, as both septic tank and constructed wetlands are simple technologies which heavily rely on natural degradation instead of active mechanical operation. Overall, the great potential to minimize the cost of septic tank+ wetland for wastewater treatment lies in reducing the sludge treatment cost, similar to the findings of environmental impacts in the LCA study.

Table 8. Comparison of costs for septic tank and septic tank + wetland

Septic Tank		Septic tank + Constructed wetland	
Septic tank	€/m³	**Septic tank**	€/m³
Fiber glass	0.0231	Fiber glass	0.0231
Piping	0.0117	Piping	0.0117
Sludge treatment	0.1032	Sludge treatment	0.1032
		Constructed wetland	
		Biocarriers	0
		Liner Polyethylene	0.0002
		Piping	0.0047
Total	**0.1380**	**Total**	**0.1429**

5. Conclusions

- The wetland with cement waste material as the substrate achieved similar pollutant removal effectiveness as that with lava stones. The wetland at the cold temperature (5°C) presented significantly lower BOD_5 and TN removals than that at the warm temperature (22°C), possibly due to limited plant sorption and biodegradation.
- The treated water in the tested wetland systems met European discharge standards (for sensitive areas) in terms of BOD_5, COD, TSS, and TN, except the TN level in the treated water from the wetland at the cold temperature.
- Integrating septic tank with constructed wetland for decentralized wastewater treatment benefits to alleviate eutrophication potential (~50%) with a small trade-off in global warming potential (~14% increase) compared to the septic tank stand-alone. Therefore, this hybrid system is mostly suitable for sensitive decentralized areas.
- The conventional practice of landfilling septic tank sludge without methane collection greatly increases global warming impact of decentralized wastewater treatment in Iceland. Thus, implementation of suitable methane collection/reuse process and adoption of nutrient recovery strategy from the treated sludge could further reduce global warming impact of wastewater treatment facilities in Iceland.
- Economic analysis revealed that the additional cost of implementing constructed wetland treatment was negligible. The overall cost of septic tank + constructed wetland is lower compared to alternative advanced treatment technologies (such as membrane filtration).

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