

Article

Elevated Vertical-Flow Constructed Wetlands for Light Greywater Treatment

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Abstract: Integrated planning of urban blue–green infrastructures is crucial to strengthen urban environmental quality and mitigate negative climate change-associated effects. It implies, however, increased water demand for irrigation, wherefore greywater (wastewater excluding wastewater from toilets and urinals) can be used, yet it requires handling for safe reuse. One treatment option is the use of constructed wetlands (CW), which have thus far not been broadly applied in inner-city districts due to large area requirements. This work investigates a novel bipartite container-based vertical-flow constructed wetland (VFCW) for the treatment of light greywater (from showers and hand wash basins) and its use as irrigation water for urban facade greenery. The VFCW consists of two compartments with 2.5 m² filter area each, filled with 75 cm zeolite-containing lava sand (0–4 mm) and 75 cm Rhine sand (0–2 mm), respectively. In short, screening has proven to be well suitable for coarse solids removal, so there is no further need to settle light greywater, which reduces overall treatment area and benefits urban application. Treated greywater complied with irrigation standards at all times, yet mixing with rainwater can help reduce salt contents, if applicable. The modular/elevated lava sand VFCW exhibited extensive nitrification, even at extremely low water temperatures, as well as mean effluent concentrations of 6.3 mg/L COD and <0.05 mg/L P_{tot}, which makes it a very promising treatment option for greywater. All in all, the modular/elevated design promotes urban application of VFCW as a multifunctional blue–green system that can help increase urban resilience.

Keywords: blue–green infrastructures; container-based; lava sand; low temperature; nature-based solutions; nitrification; phosphorus



Citation: Morandi, C.; Schreiner, G.; Moosmann, P.; Steinmetz, H. Elevated Vertical-Flow Constructed Wetlands for Light Greywater Treatment. *Water* **2021**, *13*, 2510. <https://doi.org/10.3390/w13182510>

Academic Editors: Amit Gross and Zeev Ronen

Received: 1 August 2021

Accepted: 9 September 2021

Published: 13 September 2021

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1. Introduction

Man-made climate change gives rise to higher global mean temperatures and an increased incidence of extreme weather events, e.g., heat stress, heavy rainfalls, prolonged droughts, which dramatically worsen existing local environmental stresses as a result of urbanization, such as the urban heat island effect, flooding, water shortages etc. [1,2]. Blue–green infrastructures (BGI), strategically planned networks of natural and semi-natural areas consisting of vegetative and water-related elements, offer a solution to mitigate the negative effects of climate change in cities [3]. BGI deliver a variety of ecosystem services and can provide environmental, economic and social benefits, thus leading to a higher quality of life, by e.g., increasing biodiversity and enhancing microclimate through shading, evaporative cooling, thermal insulation, etc. [4,5]. However, the implementation of BGI comes along with a significant increase in water demand, as these infrastructures require water for maintenance (irrigation, among others), which may further restrain conventional water resources, such as groundwater, surface water, bank filtrate, etc.

In order to alleviate drinking water supply systems and meet raising water demands, while simultaneously strengthening BGI in urban areas, it is imperative that unconventional

urban water resources are exploited and supplied in adequate quantity and quality, e.g., greywater (wastewater excluding toilet and urinal wastewater [6]), effluent of wastewater treatment plants (WWTP), and/or other effluents. This practice has thus far been adopted particularly in countries with high water stress, e.g., Israel (see e.g., [7,8]) and Australia (see e.g., [9,10]), among others, etc. German quality standards for irrigation water, DIN 19650 (1999) [11] and DIN 19684-10 (2009) [12] are relatively strict, when compared to international standards (see [13–15]) and may require updating, as these documents were published over a decade ago. Furthermore, rainwater is often used as an alternative water source, but is typically insufficient to meet the raising water demand in densely built-up areas due to high storage capacities required and the lack of urban space. Moreover, prolonged periods of drought, propelled by climate change, further restrain rainwater harvesting. In contrast to rainwater, greywater is produced continuously at the source, thus requiring minor storage capacities, which makes it a good complementary water resource. However, handling is necessary for safe reuse (see [11–13]).

The most widely applied technologies for greywater treatment are filtration, moving bed biofilm reactors (MBBR), membrane bioreactors (MBR), constructed wetlands (CW), among others [16]. CW are a consolidated technology for municipal wastewater treatment. For greywater treatment, vertical-flow constructed wetlands (VFCW) can meet strict chemical/physical standards for water reuse and, in terms of BOD (85% removal on average, 10 mg/L mean BOD₅ effluent concentration; see [17]) and TSS, perform as well as or better than CW for municipal wastewater [17] and usually perform best compared to other CW designs, such as free water surface and horizontal subsurface flow constructed wetlands (HFCW) [18]. Stefanakis et al. (2014) [19] reported overall VFCW performance of 85% for BOD₅ (min-max: 48–99%) and 75.2% for COD (min-max: 44–95%). In addition, CW are of simple operation, low-cost and, if planted, aesthetically pleasant, and they promote biodiversity and offer cooling effects [20–22], which are clear advantages over purely technical treatment systems. Nevertheless, CW typically require large filter areas for treatment, which have so far limited their application in urban centers [20]. In contrast, MBR and MBBR represent compact solutions for densely urbanized areas [23], yet they are more energy and resource-intensive and exhibit higher operating costs.

German guidelines DWA-A 262 (2017) [24] discourage the use of HFCW as a main treatment step for municipal wastewater and wastewater streams, e.g., greywater, since unaerated HFCW do not offer sufficient ammonium nitrogen elimination due to anaerobic milieu conditions resulting from the water-saturated operation; assuming a nitrogen-rich influent water, high ammonium concentrations (NH₄⁺-N) would be present in HFCW effluent [25], thus posing a risk to the environment. Correspondingly, there is not sufficient experience with unaerated HFCW in Germany [24]. Following the German guidelines, the present study has therefore focused on VFCW for greywater treatment. However, little focus has thus far been laid on sizing of CW for the treatment of greywater, let alone light greywater. Even though there has been progress worldwide in developing guidelines which include CW sizing for greywater treatment, German guidelines (see [24]) state that the required CW filter area for greywater treatment can be set to 50% of the area required for municipal wastewater, which is a vague statement. Additionally, in many countries, guidelines for CW designs are still limited to domestic sewage, while first guidelines to design CW to treat greywater are being elaborated.

In order to extend the field of application of CW to inner-city areas, severely affected by climate change, this study investigates an elevated container-based bipartite VFCW to treat light greywater from showers and washing basins at a construction workers' housing site in Stuttgart North in Germany. The collected light greywater is treated in two different filter chambers filled with (1) zeolite-containing lava sand (0–4 mm) and (2) conventional Rhine sand (0–2 mm), respectively. The filter innovation consists mainly of the elevated and modular design, the possibility of a simplified treatment by solely treating the light greywater fraction and the use of a novel zeolite-containing lava sand as filter media. Treated water is used as irrigation water for urban facade greenery. In

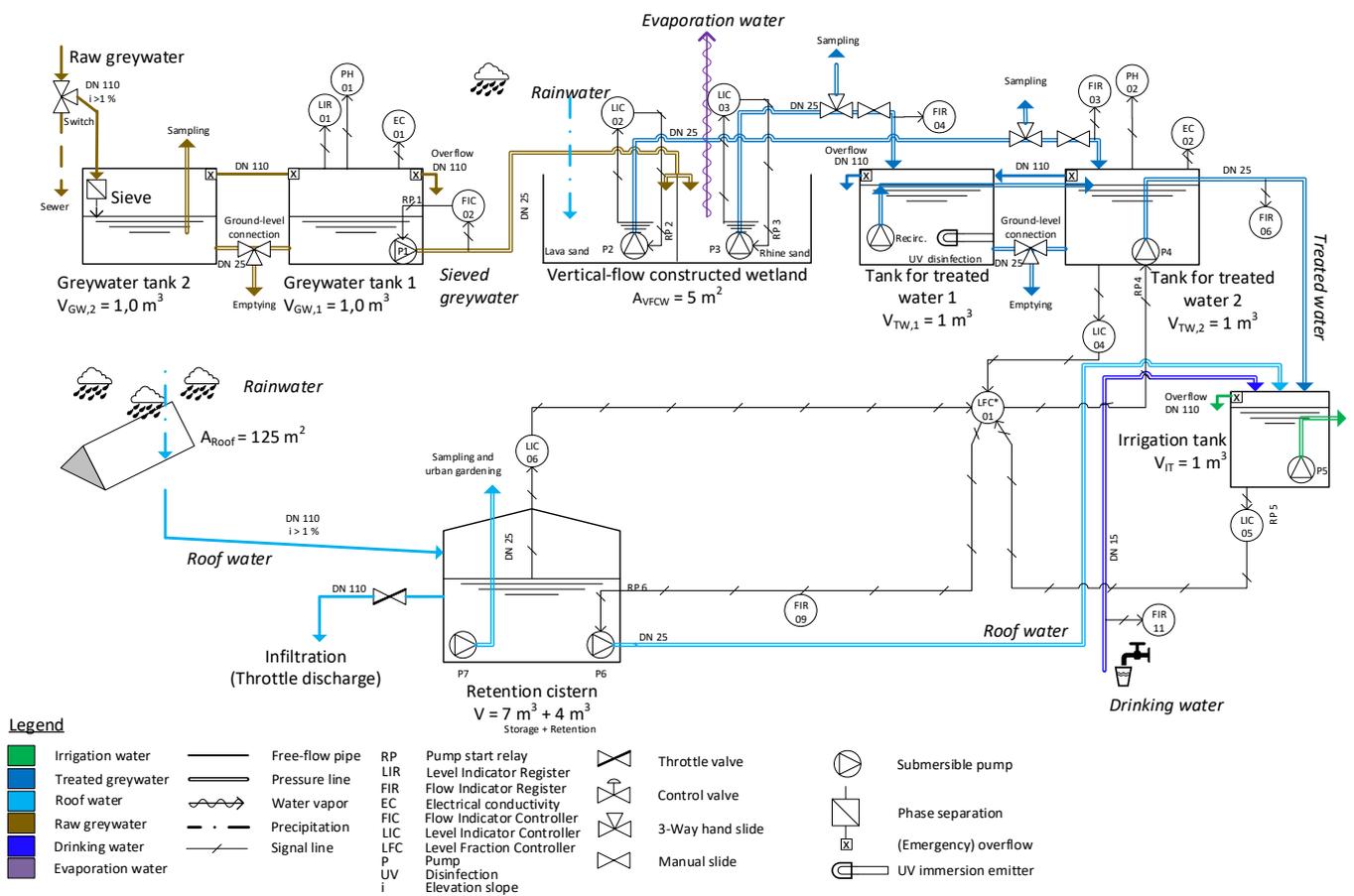
addition, the necessity of a pretreatment (e.g., multi-chamber septic tank) is discussed. Moreover, this work investigates the cleaning performances of both filter compartments at low and very low water temperatures. Subsequently, irrigation suitability is assessed by comparing effluent values with German and international irrigation standards. Based on lessons learned and treatment efficiency results, the technical feasibility of the elevated design is evaluated. Finally, recommendations are given for the application of elevated VFCW to treat light greywater in urban areas.

2. Materials and Methods

This work addressed the low-temperature operation of an elevated bipartite container-based VFCW with a total filter area of 5 m² to treat light greywater, as shown in Figure 1. Reclaimed water is applied for urban facade greenery irrigation, as depicted in Figure 1. The elevated VFCW is planted with commercially available reeds (*Phragmites australis*) and consists of two compartments with 2.5 m² filter area each, filled with 75 cm zeolite-containing lava sand (0–4 mm) and 75 cm Rhine sand (0–2 mm), respectively. Drainage layers of 25 cm gravel (2–8 mm) support the respective filter media. Lava sand was acquired from a quarry in Lissingen in Germany and exhibits an increased clay content (of >2%) as well as a natural zeolite content of approx. 10%. The Rhine sand used is commercially available fluvial sand. The VFCW is a core component of the Impulse Project Stuttgart, an urban compact demonstration and research implementation of resilient climate change adaptation measures, situated within the future Rosenstein district in Stuttgart North in Germany (further information can be found in Eisenberg et al. (2021) [26]). A schematic flow diagram of the Impulse Project Stuttgart is depicted in Scheme 1. All measuring devices and sensors are controlled via an IRRInet ACE control unit (Motech Water Solutions Ltd., Rosh Haayin, Israel).



Figure 1. Front view perspective of the modular container-based vertical-flow constructed wetland (VFCW) to treat light greywater from showers and handwash basins for use as irrigation water for the building facade (Photo: J. Rettig).



Scheme 1. Flow diagram of the Impulse Project Stuttgart with water path, volume, and area specifications as well as control logics (irrigation section not shown).

Greywater is collected from shared bathrooms (hand wash basins and showers) at a container-based workers’ housing site (see Figure 1) to which 10 apartment units are connected. Already existing separated greywater and blackwater pipes considerably reduced construction effort in retrieving greywater at the workers’ housing site. Through a free-flow pipe, light greywater is routed into a storage with a total volume capacity of 2 m³, consisting of two Intermediate Bulk Containers (IBC) (see Scheme 1). At the inlet, a screen (mesh width: 1.3 mm, Green Life GmbH, Schwerin, Germany) retains coarse solids and is cleaned regularly (once to twice a month). Although no further pretreatment is applied, the storage tanks contribute to the settling of solids in light greywater and are emptied and cleaned once every four months. Six times per day, screened light greywater is intermittently fed to the VFCW by a submersible feeding pump (Ama-Drainer N 301, KSB SE & Co. KGaA, Frankenthal, Germany). Feeding time does not exceed 1 min, so screened greywater is distributed rapidly and evenly over the entire filter area. Baffle plates, on which the distribution pipes are placed, avoid the formation of cavities into the upper filter layer that may otherwise lead to channeling. After percolating through the respective filter chamber, treated water is pumped by two flat suction pumps (Homa C80 W, HOMA Pumpenfabrik, Neunkirchen-Seelscheid, Germany) into a 2 m³ large storage (see Scheme 1), respectively, where both effluents are mixed and further disinfected by an UV immersion emitter (Aquaforte 40 W, SIBO Fluidra Netherlands B.V., Veghel, Netherlands), which is coupled to a circulation pump (ZM 280, Zehnder Group Deutschland GmbH, Lahr, Germany).

In addition to greywater, rainwater from roofs (125 m² area) is collected and stored in a 11 m³ large retention cistern (further information can be found in [26]). Excess rainwater is infiltrated in the soil to promote groundwater recharge. Level-controlled filling of

the irrigation tank is performed (see Scheme 1) in order to set a definite ratio of treated graywater to rainwater for use as irrigation water. Both pH and electrical conductivity (EC) are monitored continuously in raw and treated greywater by pH (202705, JUMO GmbH & Co. KG, Fulda, Germany) and EC sensors (BlackLine CR-EC, JUMO GmbH & Co. KG, Fulda, Germany), attached to immersion fittings. However, it is not possible to differentiate between effluents, as both tanks for treated water are hydraulically connected, as can be inferred from Scheme 1, so this data has not been included in the present work. Alternatively, on sampling days, pH and EC of raw greywater and both effluents are also determined by WTW portable meters (Xylem Analytics Germany Sales GmbH & Co. KG, Weilheim, Germany). Additionally, levels and volume flows are continuously measured by ultrasonic level meters (AU006, Autoson GmbH, Essen, Germany) and, within the CW effluent shafts, by pressure level sensors (AquaBar II, Nivus GmbH, Eppingen, Germany) as well as by water meters (HidroJet $\frac{1}{2}$ " , Hidroconta S. A., Murcia, Spain) and, at the VFCW inlet, by a magnetic-inductive flow meter (SM9000, ifm electronic GmbH, Essen, Germany) respectively, as can be inferred from Scheme 1. By change in filling level (raw greywater storage), daily greywater volume flows could be determined, provided that overflow did not occur.

According to the outside air temperature and the feeding volume flow set, VFCW operation was categorized into different operating phases, shown in Table 1; respective hydraulic and COD (chemical oxygen demand) surface loading rates are given for each phase and filter chamber. During Phase 5b, the VFCW was taken out of operation for one week as precaution measure to avoid frost damages on pumps and sensors.

Table 1. Operating phases for the vertical-flow constructed wetland, from July 2020 to March 2021 in Stuttgart North, Germany.

Operating Phase	Period (dd.mm.yy)	Filter Chamber	Hydraulic Surface Loading Rate in L/(m ² ·d)	COD Surface Loading Rate in g/(m ² ·d)	Outdoor Air Temperature, Daily Mean (Min/Max) in °C
1 (start-up)	11.07.2020– 08.09.2020	Lava sand	80 (set)	-	21.2
		Rhine sand	80 (set)	-	(11.3/31.3)
2	09.09.2020– 18.10.2020	Lava sand	73	18	13.8
		Rhine sand	82	20	(8.4/22.6)
3	19.10.2020– 29.11.2020	Lava sand	63	19	7.9
		Rhine sand	80	24	(3.2/15.1)
4a	30.11.2020– 21.11.2020	Lava sand	66	37	2.8
		Rhine sand	83	46	(−0.2/7.0)
4b	22.12.2020– 11.01.2021	Lava sand	18	8	1.6
		Rhine sand	22	9	(−1.3/4.9)
4c	12.01.2021– 27.01.2021	Lava sand	65	15	1.4
		Rhine sand	83	19	(−1.9/4.9)
5a	28.01.2021– 10.02.2021	Lava sand	43	10	4.2
		Rhine sand	62	14	(1.1/7.6)
5b	11.02.2021– 17.02.2021	Lava sand	out of operation		−2.0
		Rhine sand			(−8.8/7.5)
5c	18.02.2021– 15.03.2021	Lava sand	46	10	6.0
		Rhine sand	56	12	(−0.4/16.6)

Raw greywater and treated greywater are sampled on a weekly basis (except for holidays); corresponding sampling points are shown in Scheme 1. Sampling of raw greywater is performed directly from the storage tank by means of a sampling scoop attached to a rod, as a multiday composite sample, while treated greywater by each filter compartment is drawn through a respective sampling valve connected to the effluent shaft (see Scheme 1) as a 24 h composite sample, by temporarily impounding the drainage layers.

Greywater analysis is carried out in a container lab on-site using Hach Lange LCK cuvette tests and a photometer DR 1900 (Hach Lange GmbH, Düsseldorf, Germany), except for the cations K^+ , Mg^{2+} , Ca^{2+} and Na^+ , which are conserved, as explained below, and analyzed by ion chromatography (930 Compact IC Flex, Deutsche METROHM GmbH & Co. KG, Filderstadt, Germany) in the lab facilities of the Technische Universität Kaiserslautern. COD, N_{tot} , P_{tot} , NH_4^+-N , $NO_3^- -N$, $PO_4^{3-} -P$ and the investigated cations are measured mostly by double determination, exceptions represent $NO_3^- -N$ in screened greywater and N_{tot} in both effluents, which were analyzed by simple determination. $NO_2^- -N$, Cl^- , SO_4^{2-} as well as cationic, anionic, and non-ionic surfactants are measured by simple determination, except for chloride in screened greywater, which is analyzed by double determination. All parameters, except for Cl^- , SO_4^{2-} and surfactants, are determined on a weekly basis, if the opposite is not explicitly stated. In an attempt to reduce the use of chemicals and save labor time, the analysis frequency for surfactants, chloride, and sulfate was set lower than for the remaining parameters, as surfactant determination is time-consuming and chlorides and sulfates are not removed or substantially transformed in the filter. The unfiltered samples for the sum parameters COD, N_{tot} und P_{tot} are chemical-thermally digested in a thermostat LT200 (Hach Lange GmbH, Düsseldorf, Germany). Additionally, surfactants are analyzed from the unfiltered sample. Samples for dissolved parameters are filtered with a 0.45 μm Minisart RC syringe pre-filter (Sartorius AG, Göttingen, Germany). After filtration, the samples for cation analysis are acidified with concentrated nitric acid to a pH of 2.5 to 3.5, deep-frozen at $-18^\circ C$ and analyzed at a later date. The sodium adsorption ratio (SAR) is calculated according to DIN 19684-10 [12]. The biological oxygen demand (BOD_5) is not investigated, yet expected BOD_5 concentration ranges can be estimated based on the determined COD concentrations and typical COD/ BOD_5 ratios from the scientific literature.

In this work, while dealing with values below the limit of determination (LOD), a measured value $<LOD$ was replaced by a numerical value ($0.5 \times LOD$) for data series with a sufficient share (50%) on measured values $>LOD$ only, in accordance to [27].

3. Results and Discussion

3.1. Light Greywater Characterization

Table 2 shows the composition and volume flow of screened light greywater from the temporary workers' accommodation (VFCW influent). An estimated light greywater volume flow of 48 L per person and day highlights the considerable water potential in such facilities, yet it must be noted that only little greywater was produced on weekends and during company vacations (see Table 2). The varying volume flows can be e.g., counterbalanced by sufficiently large storage tanks (e.g., three days volumes). The median COD concentration for screened light greywater amounted to 258 mg/L, as can be inferred from Table 2, and is similar to literature values for household light greywater (283 mg/L COD [28]); the higher mean value of 328 mg/L COD is attributable to two outliers of 1039 mg/L and 779 mg/L, which fell within the range of highly polluted greywater (258–1021 mg/L [28]). Using a calculated COD/ BOD_5 ratio in light greywater of 2.05 (see [28]), a BOD_5 concentration of 126 mg/L can be estimated, which is found to lie within the typical range for light greywater (61–188 mg/L, see [28]). Despite sieving, a N_{tot} mean concentration of 28.3 mg/L (see Table 2) was observed, which significantly exceeded expected values for light greywater at the household level (10 mg/L N_{tot} , see [28]). The high nitrogen content may be an indicative of partial urine contamination in the construction workers' shower water, yet further investigation is needed to support this proposition. On the other hand, phosphorus concentrations (1.9 ± 0.5 mg/L, see Table 2) were lower than the expected literature values (2.8 mg/L P_{tot} [8], 3.3 mg/L P_{tot} [28]) for bathroom greywater. This may be related to the increased use of low-phosphate detergents and cleaning agents in the workers' housing, exemplified by the alkaline high concentrate Force F (Layer-Chemie GmbH, Leingarten, Germany), which directly affects greywater composition. The restricted use of phosphates and phosphate compounds in such products is enshrined in

German law by the Detergents and Cleaning Agents Act [29]. The pH of 8.4 ± 0.3 (see Table 2) lied at the upper end of the expected range for light greywater (5–8.6 [28]), which among others can be attributed by the use of alkaline cleaning agents (Force F has a pH value of 13.5). The electrical conductivity of tap water at the Impulse Project (Stuttgart North) was determined to $522 \pm 13 \mu\text{S}/\text{cm}$ ($n = 5$), which elucidates greywater salinization ($\text{EC} = 737 \mu\text{S}/\text{cm}$ on average; see Table 2) through the use of cleaning and personal care products. All in all, the results indicate that greywater characterization is critical for VFCW sizing and project success, as quality can differ significantly from expected literature values.

Table 2. Volume flow and composition of screened light greywater (showers and washbasins) from container-based workers' accommodations in Stuttgart North.

Parameter	Unity	Mean Value \pm Std. Dev.	Median	Min–Max	<i>n</i>
Volume flow	L/(p-d)	48 ± 22	42	0.4–82	41
COD	mg/L	328 ± 211	258	197–1039	20
N_{tot}	mg/L	28.3 ± 7.1	27.9	19.0–46.8	20
P_{tot}	mg/L	1.9 ± 0.5	1.8	1.3–3.2	20
pH	-	8.4 ± 0.3	8.5	7.6–8.8	18
EC	$\mu\text{S}/\text{cm}$	737 ± 51	722	678–837	8

3.2. Plant Development

The growth and decay of the VFCW reeds during different operating phases can be followed in Figure 2. Already during the first year of operation (see October 2020), microphytes grew extremely well, thus transforming the “technical VCFW” into a genuine blue–green element, which can be easily integrated in the urban landscape design, thus reducing disputes over land developments in inner-city areas.



Figure 2. VFCW in different operating phases (Photos: J. Rettig; P. Moosmann).

3.3. Pretreatment Requirement for Light Greywater

During VFCW operation, no operational malfunction or failure due to filter clogging has thus far been reported while treating screened light greywater from shared bathrooms. This leads to the conclusion that screening and non-targeted sedimentation in the storage tanks are suitable for removing solid particles from light greywater, so no complex pre-

treatment (e.g., multi chamber septic tank or settling pond, as recommended in German technical regulations [24]) is required. This finding is explicitly valid for light greywater without kitchen and/or washing machine wastewater only and can significantly reduce area requirements for urban application of VFCW. On a larger scale, the operating effort could be significantly reduced by e.g., using self-cleaning screens or rakes and funnel-shaped tank bases with an outlet tap at the bottom to release the solid layer into the sewer on demand.

3.4. Reduction of Organic Matter

Table 3 gives a general overview of influent and effluent values achieved by both filter chambers. Regardless of the operating phase (see Table 3), COD cleaning performances of both lava sand (6.3 ± 3.0 mg/L) and Rhine sand filter (11.3 ± 3.9 mg/L) have proven to be very promising (see Table 3). COD load was reduced on average by 98% in the lava sand chamber and by 96% in the Rhine sand compartment, thus outperforming wetlands for greywater treatment (see e.g., [17,18]) and municipal water treatment (see e.g., [19,25]). This finding may be due to the treatment of exclusively light greywater, which benefits VFCW operation. Furthermore, COD effluent values remained stable even at very low water temperatures (see Tables 1 and 3). In January 2021, temperatures reached 1.4 °C in both filter effluents. In all operating phases, COD concentrations were found to lie far below 60 mg/L COD, above which, according to DIN 19650 [11], a hygienic-microbiological risk cannot be excluded without further measurements. Regarding COD reduction, the lava sand filter performed better than the conventional Rhine sand filter, which may be partially related to the fact that the lava sand filter was operated at slightly lower hydraulic surface loading rates than the Rhine sand filter (see Table 1) due to a height difference between the inlet distribution pipes, which has now been corrected. Most importantly, the better COD efficiencies can presumably be attributed to the higher water-binding capacity of the zeolite-containing lava sand, when compared to conventional fluvial sands. Upon contact with water, the higher water absorption capacity leads to swelling of the grain structure and a consequent contraction of pore spaces. This equalizes the distribution of the wastewater within the filter media and reduces hydraulic conductivity, which in turn increases contact time between water and microorganisms [30], thus enhancing treatment efficiency.

Table 3. General overview of influent and effluent values achieved by the lava sand (0–4 mm) and Rhine sand (0–2 mm) filters treating screened light greywater from shared showers and hand wash basins at temporary construction workers' housing in Stuttgart North, in comparison with standards for irrigation water.

Parameter	Unit	Screened Greywater			Lava Sand Chamber HLR = 18–73 L/(m ² ·d) OLR = 8–37 gCOD/(m ² ·d)			Rhine Sand Chamber HLR = 22–83 L/(m ² ·d) OLR = 9–46 gCOD/(m ² ·d)			Irrigation Water Standards
		Mean Value ± Std. Dev.	Median (Min–Max)	n	Mean Value ± Std. Dev.	Median (Min–Max)	n	Mean Value ± Std. Dev.	Median (Min–Max)	n	
COD	mg/L	328 ± 211	258 (197–1039)	20	6.3 ± 3.0	6.0 (2.5–16.8)	20	11.3 ± 3.9	11.7 (2.5–17.9)	20	<60 mg/L [11] due to microbiological-hygienic concerns
N _{tot}	mg/L	28.3 ± 7.1	27.9 (19.0–46.8)	20	25.5 ± 8.8	25.8 (8.9–37.7)	20	24.4 ± 6.7	23.9 (10–37.3)	20	-
P _{tot}	mg/L	1.9 ± 0.5	1.8 (1.3–3.2)	20	<0.05		20	0.91 ± 0.36	0.94 (0.16–1.37)	20	-
pH	-	8.4 ± 0.3	8.5 (7.6–8.8)	18	7.5 ± 0.2	7.5 (7.1–7.7)	17	7.2 ± 0.1	7.3 (6.9–7.4)	17	6–8 [12]
EC	µS/cm	737 ± 51	722 (678–837)	8	872 ± 42	877 (807–943)	9	860 ± 36	858 (803–902)	9	Medium salt tolerance: 300–800 µS/cm [12]; salt sensitive crops: <1400 µS/cm [13]
PO ₄ ³⁻ -P	mg/L	1.2 ± 0.5	1.0 (0.6–2.3)	20	<0.05–0.08 ^D		20	0.93 ± 0.35	0.98 (0.14–1.5)	20	-
NO ₃ ⁻ -N	mg/L	<0.23–0.8 ^A		6	23.9 ± 8.7	23.3 (8.2–38.2)	20	19.7 ± 5.5	19.6 (9.6–29.1)	20	-
NO ₂ ⁻ -N	mg/L	<0.015		1	<0.015		6	0.40 ± 0.32	0.33 (0.06–0.95)	10	-
NH ₄ ⁺ -N	mg/L	13.9 ± 5.6	12.8 (2.8–25.9)	20	0.4 ± 0.3 ^E	0.3 (0.05–1.0)	17	2.3 ± 1.6 ^I	1.7 (0.5–4.9)	18	<1 mg/L (NH ₄ ⁺) [11] due to microbiological-hygienic concerns
SO ₄ ²⁻	mg/L	<40–49.7 ^B		19	42 ± 16 ^F	50 (20–57)	6	46 ± 17 ^J	53 (20–62)	7	<250 mg/L [31], otherwise corrosive
Cl ⁻	mg/L	58 ± 8	58 (44–80)	18	56 ± 8	57 (44–69)	18	56 ± 8	57 (42–66)	16	Suitable for nearly all plants: <70 mg/L [12]; salt sensitive crops: <250 mg/L [13]

Table 3. Cont.

Parameter	Unit	Screened Greywater			Lava Sand Chamber HLR = 18–73 L/(m ² ·d) OLR = 8–37 g _{COD} /(m ² ·d)			Rhine Sand Chamber HLR = 22–83 L/(m ² ·d) OLR = 9–46 g _{COD} /(m ² ·d)			Irrigation Water Standards
		Mean Value ± Std. Dev.	Median (Min–Max)	<i>n</i>	Mean Value ± Std. Dev.	Median (Min–Max)	<i>n</i>	Mean Value ± Std. Dev.	Median (Min–Max)	<i>n</i>	
Na ⁺	mg/L	26.3 ± 6.2	27.4 (10.8–38.6)	19	11.8 ± 6.7 ^G	11.0 (5.0–35)	18	28.3 ± 7.8 ^K	27.9 (5.0–38.6)	19	<30 mg/L [12]; salt sensitive crops: <150 mg/L [13]
Ca ²⁺	mg/L	63 ± 12	64 (35–80)	19	95 ± 16	100 (58–112)	18	94 ± 16	96 (38–116)	19	-
Mg ²⁺	mg/L	9.5 ± 2.0	10.4 (5.0–12.4)	19	17.0 ± 3.0	18.2 (11.3–21.2)	18	10.4 ± 2.0	11.0 (4.7–12.7)	19	-
K ⁺	mg/L	<10–72 ^C		19	23 ± 16	20.7 (10.4–86)	18	<10–24 ^L		19	-
Non-ionic surfactants	mg/L	6.7 ± 7.0	4.1 (1.8–16.8)	4	<0.2		4	<0.2–0.3 ^M		4	-
cationic surfactants	mg/L	0.9 ± 0.2	0.9 (0.7–1.2)	4	<0.2–0.6 ^H		4	0.2–0.7 ^N		4	-
anionic surfactants	mg/L	12.9 ± 2.5	13.7 (9.3–14.9)	4	0.5 ± 0.1	0.5 (0.4–0.5)	4	0.9 ± 0.2	0.9 (0.6–1.0)	4	-
SAR	(mmol/L) ^{1/2}	1.6 ± 0.3	1.6 (0.9–2.3)	19	0.6 ± 0.3	0.5 (0.3–1.7)	18	1.4 ± 0.3	1.4 (0.4–1.9)	18	<6 (mmol/L) ^{1/2} [12], suitable for irrigation of nearly all soil types

^A 4 out of 6 values < LOD, mean value within measuring range: 0.6 mg/L, ^B 15 out of 19 values < LOD; mean value within measuring range: 44 mg/L, ^C 14 out of 19 values < LOD, mean value within measuring range: 24.2 mg/L, ^D 18 out of 20 values < LOD, mean value within measuring range: 0.08 mg/L, ^E 6 out of 17 values < LOD, mean value within measuring range: 0.3 mg/L, ^F 2 out of 6 values < LOD, mean value within measuring range: 53.3 mg/L, ^G 4 out of 18 values < LOD, mean value within measuring range: 13.7 mg/L, ^H 3 out of 4 values < LOD, only on 08.03.2021: 0.7 mg/L, ^I 3 out of 18 values < LOD, mean value within measuring range: 2.6 mg/L, ^J 2 out of 7 values < LOD, mean value within measuring range: 56.4 mg/L, ^K 1 value < LOD on 10.19.2020, ^L 11 out of 19 of values < LOD, mean value within measuring range: 12.4 mg/L, ^M 2 out of 4 values < LOD, only on 30.11.2020: 0.29 mg/L und am 18.01.2021: 0.3 mg/L, ^N 2 out of 4 values < LOD, only on 18.01.2021: 0.22 mg/L and on 08.03.2021: 0.7 mg/L.

Assuming a COD/BOD₅ ratio of 2.0 [28] at the inlet as well as typical VFCW overall removal performances of 85% for BOD₅ and 75.2% for COD [19], a COD/BOD₅ ratio of 3.4 can be estimated for the effluent water. Hence, estimated BOD₅ concentrations lower than 1.8 ± 0.9 mg/L and 3.3 ± 1.1 mg/L can be expected for the lava sand and the Rhine sand effluent, respectively, as the overall COD removal in this study reached 98%, which is significantly higher than reported literature values. These outstanding concentrations fall below several applicable standards for the unrestricted use of treated wastewater as irrigation water in Germany and elsewhere (Germany: BOD₅ < 10 mg/L, see DIN 19650 (1999) [11]; International: BOD₅ < 5 mg/L for very high quality treated wastewater, see ISO 16075-1 (2020) [13]; International: for instance, BOD₅ < 10 mg/L, depending on the requirements of the local regulatory agency, see WHO (2006) [14]; European Union: BOD₅ < 10 mg/L for treated water for agricultural irrigation, see EU 2020/741 (2020) [15]). The achieved effluent values show that treating solely light greywater can enhance VFCW performance, as both filter chambers outperform reported efficiencies from the scientific literature (see e.g., [17,18]).

3.5. Nitrification at Low Temperatures

With regards to nitrification at low temperatures, it can be stated that elevated lava sand VFCW is, in principle, more suitable than the Rhine sand counterpart, yet fluvialite sands are largely commercially available and low-cost. On average, N_{tot} concentrations in the lava sand filter effluent amounted to 25.5 ± 8.8 mg/L, from which 23.9 ± 8.7 mg/L were present as NO₃⁻-N (see Table 3). Nitrates improve water irrigation quality as they can be considered in the fertilizer balance. However, caution is recommended in case of water infiltration, as high nitrates concentration can compromise quality of drinking water obtained from aquifers. Only minor ammonium nitrogen concentrations (0.4 ± 0.3 mg/L, min-max: 0.05–1.0 mg/L) were found in the lava sand chamber effluent during the coldest operating phases, while no nitrite was detectable. Lava sand disposes of a higher cation exchange capacity than conventional fluvialite sands [30], which seems to enhance ammonium retention within the filter media, which in turn, combined with an increased contact time between nitrifying bacteria and greywater due to the ability of the zeolite-containing lava sand to swell, promotes extensive nitrification at all times, even at very low water temperatures near the freezing point. This is an important finding as nitrification is very limited when wastewater temperature is below 10 °C [32]. In contrast, Rhine sand effluent was found to entail 24.4 ± 6.7 mg/L N_{tot} (of which only 19.7 ± 5.5 mg/L were determined as NO₃⁻-N) as well as increased concentrations of nitrite (0.40 ± 0.32 mg/L NO₂⁻-N, reaching up to 0.95 mg/L, see Table 3) and ammonium nitrogen (2.3 ± 1.6 mg/L; min-max: 0.5–4.9 mg/L), despite reduced feeding in Phases 5a and 5c (see Table 1). However, a complete collapse of the nitrification was not observed. Incomplete nitrification can be ascribed to the very low water temperatures at the inlet, triggered by the outdoor placement of all storage tanks, in combination with the elevated/unprotected VFCW design (despite insulation), which lacks heat from the soil (when compared with conventional filters that are embedded in the ground). All in all, the authors strongly recommend the use of elevated container-based VFCW filled with zeolite-containing lava sands (0–4 mm) to treat light greywater from showers and hand wash basins. It is advisable to insulate both the VFCW and the storage tanks to avoid freezing hazard. This opens up diversified planning options for urban areas (e.g., placement of VFCW on paved courtyards, roofs, carports, temporary uses etc.), thus significantly mitigating conflicts over competition for land. For conventional fluvialite sand filters, however, there may be a need to embed them in the ground (conventional design) to avoid low temperatures in the winter that limit nitrification.

3.6. Phosphorus Retention

With respect to phosphorus, a significant decrease in elimination performance in the Rhine sand filter was observed over time, which is consistent with findings from the

scientific literature (see e.g., [19]). Elimination rates for P_{tot} load varied from 83.4% in Phase 2, 56.8% in Phase 4b to 18.4% in Phase 5c (see Table 1). In contrast, the lava sand compartment exhibited P_{tot} effluent values <0.05 mg/L (LOD) at all times (P elimination rates $>97\%$), which corroborates literature findings of enhanced phosphorus removal in zeolite-containing lava sand CW that treat municipal wastewater from combined sewer systems in Germany, even after operating times of years [30,33]. P removal is improved by the high natural zeolite content of lava sands [33] and the increased contact time between VFCW and porous media in the filter [30].

To the authors' best knowledge, this is the first time that both outstanding COD effluent values (6.3 ± 3.0 mg/L; min-max: 2.5–16.8 mg/L) and extremely low-phosphorus effluents (<0.05 mg/L P_{tot}) are reported for a single-pass VFCW for greywater treatment that has not been explicitly designed for phosphorus elimination. This makes natural zeolite-containing lava sand (0–4 mm) a very promising filter material for CW operation. German technical regulations (see DWA-A 262 (2017) [24]) recommend the use of lava sand filters for municipal wastewater treatment, which will potentially propel its large-scale implementation. Further investigation is, however, required to assess hygienic-microbiological risks and the presence of micropollutants in the effluent.

3.7. Compliance with Irrigation Water Standards and Further Remarks

As can be inferred from Table 3, all further investigated parameters in both VFCW effluents complied with irrigation water standards at all times: pH values within 6–8 [12], sulfate concentrations far below 250 mg/L [31], chloride contents <70 mg/L [12]; sodium concentrations <30 mg/L [12] and SAR values <6 (mmol/L) $^{1/2}$ [12]. The reduction of pH 8.4 at the inlet to more neutral values in the effluent can possibly be ascribed to a combination of alkalinity consumption through nitrification [34] and exudation of H^+ /organic acids by roots (see e.g., [35,36]). In addition, the EC can become a problem, which was found to be slightly higher than the salt tolerance range for plants with medium salt tolerance [12], yet both effluent values fell far short of the ISO 16075-1 [13] limit recommendation of 1400 $\mu\text{S}/\text{cm}$. In any case, the electrical conductivity varies site-specifically. If needed, treated greywater can be blended with rainwater (e.g., from roofs) to reduce EC to a suitable value below 800 $\mu\text{S}/\text{cm}$, which is the upper limit stipulated in DIN 19684-10 [12] for plants with moderate salt tolerance. At the Impulse Project, irrigation water for facade greenings is a mixture of 75/25 (vol. %) treated greywater/rainwater.

Treated greywater entails nutrient contents (N, K, P) that can reduce fertilizer demand, thus improving crop fertilization, yet zeolite-containing lava sand significantly retains phosphorus. Furthermore, under the investigated conditions, lava sand seemed to release Mg^{2+} , Ca^{2+} , K^+ into the water, whereas Na^+ was partially retained (see Table 3); average Mg^{2+} concentrations went from 9.5 mg/L at the inlet up to 17.0 mg/L in the effluent, while Ca^{2+} contents increased from 65 mg/L up to 95 mg/L in the effluent (Table 3). Ca^{2+} leaching was also observed in the Rhine sand effluent (see Table 3). K^+ contents at the inlet were mostly <10 mg/L (LOD) and reached 23 mg/L K^+ on average in the lava sand effluent. Potassium is a macronutrient and can thus improve irrigation water quality as well. In contrast, Na^+ concentrations were reduced by the lava sand filter from 26 mg/L at the inlet to 11.8 mg/L on average, which is consistent with the SAR reduction from 1.6 (mmol/L) $^{1/2}$ to 0.6 (mmol/L) $^{1/2}$ by the lava sand filter. This directly benefits soil irrigation. The release of Mg^{2+} (only valid for lava sand) and Ca^{2+} into the effluent water may partially elucidate the increase in EC from 737 ± 51 $\mu\text{S}/\text{cm}$ at the inlet up to 872 ± 42 $\mu\text{S}/\text{cm}$ (lava sand) and 860 ± 36 $\mu\text{S}/\text{cm}$ (Rhine sand). Moreover, non-ionic and anionic surfactants were degraded very well by both filter substrates with elimination rates $>93\%$. Cationic surfactants, which are however only present in traces in light greywater, were eliminated to 70–78%. This highlights the high quality of the treated water.

4. Conclusions

The volume flow of light greywater from showers and hand wash basins at a temporary construction workers' housing site in Germany was estimated to be 48 L per person and day, thus emphasizing the considerable potential for water reclamation in such facilities. Characterization of greywater has proven to be critical for correct CW sizing, as volume flows and composition can vary significantly from expected values. In addition, screening was shown to be well suitable as a pretreatment step for light greywater (excluding kitchen wastewater and water from washing machines). Hence, there is no further need of settling light greywater (e.g., in a multi-chamber septic tank), which results in a lower total treatment system area, thus promoting VFCW application in built-up inner-city areas. Treated light greywater in both lava sand (0–4 mm) and Rhine sand (0–2 mm) filters complied with irrigation standards at all times, yet rainwater blending can help reduce salt contents, if applicable. Furthermore, treated greywater can be an adequate complementary nutrient source for crop irrigation. Besides, the elevated container-based VFCW filled with conventional fluvial sand exhibited incomplete nitrification at low water temperatures; therefore, there may be a need to embed it into ground (conventional design). In contrast, the elevated lava sand VFCW showed outstanding COD cleaning performances (effluent values: 6.3 ± 3.0 mg/L), extensive nitrification even at extremely low water temperatures and enhanced phosphorus retention (effluent values: <0.05 mg/L P_{tot}), which makes the zeolite-containing lava sand (0–4 mm) a very promising filter material for greywater treatment. All in all, the authors of this study strongly recommend the elevated container-based design for lava sand filters to treat light greywater, as this opens up new opportunities in urban planning, thus mitigating disputes over land in built-up urban areas. Finally, the Stuttgart Impulse Project demonstrates that measures for integrated blue–green planning can be successfully implemented in inner-city districts within a confined space, thus significantly contributing to urban resilience.

Future research includes the VFCW operation at higher organic and hydraulic surface loading rates to determine the required filter area for light greywater treatment, which is likely to lie below 0.5 m² per person, and the need for amendments in the technical regulations. There is also a need to investigate phosphorus retention in the lava sand compartment in the long-term to determine when and to what extent a phosphorus breakthrough may take place. Additionally, investigations into the VFCW performance on the removal of hygienic-microbiological parameters and selected micropollutants are also scope of ongoing research. Future research will also comprise the sporadic analysis of BOD₅ at the wetland inlet and outlet to validate the theoretical assumptions.

Author Contributions: Conceptualization, C.M. and H.S.; methodology C.M., P.M., and G.S.; investigation, C.M., P.M., and G.S.; data processing, P.M. and G.S.; writing—original draft preparation, C.M. and G.S.; writing—review and editing, C.M., G.S., and H.S.; project administration, H.S.; funding acquisition, C.M. and H.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the German Federal Ministry for Education and Research (BMBF), grant number 01LR1705B1.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank all the Impulse Project Stuttgart's Partners for the productive cooperation. Special thanks are due to Ingo Bruch for all the knowledge shared.

Conflicts of Interest: The authors declare no conflict of interest.

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