Towards water self-sufficiency: pilot operation of an off-grid water cycle based on rainwater harvesting and low-tech, biological greywater treatment in an inhabited demonstration house in Switzerland (KREIS-Haus)

D. Buehler*,**, R. Junge** and D. Rousseau*

* Department of Green Chemistry and Technology, Ghent University Campus Kortrijk, Sint-Martens-Latemlaan 2B, 8500 Kortrijk, Belgium (E-mail: *devi.buhler@ugent.be*; *diederik.rousseau@ugent.be*)
** Institute of Natural Resource Sciences, Zurich University of Applied Sciences, Grüentalstrasse 22, 8820 Wädenswil, Switzerland (E-mail: *devi.buehler@zhaw.ch, ranka.junge2@zhaw.ch)*)

Abstract
With the aim to address water scarcity and support the sustainable use and treatment of (waste-) water, this study examines a self-sufficient, off-grid water system in the inhabited demonstration house “KREIS-Haus”. The water system is based on rainwater harvesting and greywater treatment with a low-tech treatment implementing submerged, attached biofilm growth. Treated rainwater is used as drinking water and treated greywater is used for the washing machine and irrigation of the rooftop garden. In an experimental period of 17 weeks, several water quality parameters were analyzed once per week before and after the rainwater and greywater treatment. Comparing the results to Swiss/EU regulation and literature, the treated greywater is suitable for irrigation and laundry. However, the treated rainwater did not always meet the required limit values for turbidity and TOC. The greywater treatment unit achieved removal rates of 92% for COD and 98% for turbidity, and no accumulation of substances was observed in the treated greywater. Water self-sufficiency was at 100% over the whole experimental period, and excess water pumped out of the system met the standard for discharge into a water body. While these first results indicate a promising approach to the water concept, more long-term monitoring and testing with higher occupancy is needed.

Keywords
Biological wastewater treatment; greywater treatment, rainwater harvesting, self-sufficiency, wastewater reuse

INTRODUCTION

Freshwater is becoming an increasingly scarce resource due to global trends such as urbanization, climate change and population growth (UNESCO, 2017). Therefore, the 2017 United Nations Global Water Report (2017) highlights the importance of wastewater reuse as a strategy to address water scarcity. A number of studies have examined local greywater treatment and its reuse potential for non-potable applications such as toilet flushing or irrigation (Chrispim & Nolasco, 2017; Masi et al., 2016; Radingoana et al., 2020; Yoonus & Al-Ghamdi, 2020). With the aim to develop fully water self-sufficient systems, greywater treatment and reuse can be combined with rainwater harvesting for drinking water supply. By doing so, no centralized infrastructure for (waste-) water is needed. The inhabited demonstration house “KREIS-Haus” (German for Klima- und Ressourcen-effizientes Suffizienz Haus, English: climate and resource efficient sufficiency house), located in Feldbach Switzerland, implements completely closed resource cycles on building level on approx. 40m^2. The house is built in three parts: the tempered living unit, the adjacent conservatory with rooftop garden, and the technology room. Beside a range of sustainable building materials and an energy system based on solar energy, the house implements an off-grid water system. The aim of this study was to examine the water cycle in KREIS-Haus in terms of treatment performance, output water quality and compliance with legal standards, and degree of water self-sufficiency.

MATERIALS AND METHODS

Water supply and management of the examined "KREIS-Haus" is based on rainwater collection and greywater treatment and reuse. Rainwater from the 77m^2 roof is collected in a 3m^3 tank and processed into drinking water by a series of filtration and treatment steps including a particle filter, activated carbon and UV-LED (Figure 1). Thanks to the dry separating toilet, no wastewater is produced from the toilet. All faucets and the shower are highly water efficient. The lightly polluted greywater from the bathroom (sink, shower), washing machine and kitchen is collected in a 1.5m^3 tank. From there, the greywater is pumped once per day into the in-house treatment unit (own development) in the form of a mobile box of 210 x 70 x 150cm (LxWxH). The treatment technology is based on submerged, aerobic, attached biofilm growth in a low-tech process with the aim to require minimal maintenance, energy, as well as investment and running costs. The technology is a further development based on the findings of the previous study of Buehler et al. (2021). The treated greywater is reused in the house for the washing machine and irrigation of the rooftop garden. Not used treated greywater flows back into the greywater tank. When the greywater tank is full, the water flows into the overflow tank (1.5m^3), which needs to be manually emptied. All tanks are located in the ground under the house. Prior to the sampling period of this study, the house was intermittently inhabited, and the treatment system was operational for 9 months. The sampling period was carried from 22 July 2022 to 14 November 2022 (17 weeks). The house was inhabited by changing visitors staying between 2 to 12 days. On average, the house was occupied by 2 people on 3 days per week. Eco-friendly detergents and body care products were provided but their use was not enforced. The water quality parameters were analyzed once per week before and after the rainwater and greywater treatment.

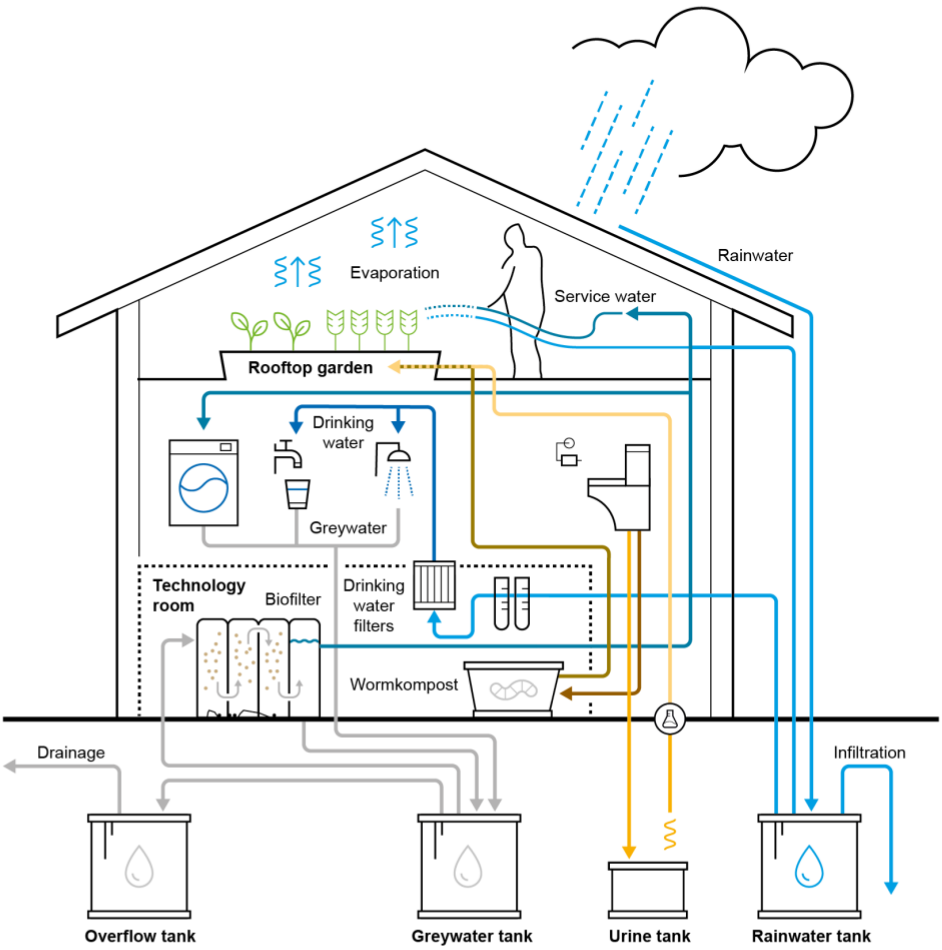

Figure 1. Off-grid water cycle in the KREIS-Haus based on rainwater collection and greywater treatment and reuse

RESULTS AND DISCUSSION

According to the EU regulation 2020/741 for water reuse (European Commission, 2020), the treated greywater is suitable for agricultural irrigation of quality class A in terms of the measured mean values for turbidity (1.2 FNU, Table 1), BOD_5 (5.3 mg/L, Table 1), *E.coli* (0 CFU/100ml) and Legionella (>20 CFU/L). The treated greywater is also suitable for laundry according to literature values (Ciabatti et al., 2009; Gross et al., 2015; Hoinkis & Panten, 2008) in terms of turbidity, COD, pH and EC. The greywater treatment unit achieved removal rates (92% for COD, 87% for BOD_5 and 98% for turbidity) comparable to other well performing attached growth systems (Khalil & Liu, 2021). BOD/COD ratio was before and after the greywater treatment at 0.3, indicating that both biological and physical processes took place. However, biological activity would need to be verified by other methods such as FDA. Figure 1 shows that the pollution loads in greywater fluctuate with the occupancy of the house. Since the values for 'Greywater' do not reflect raw greywater but mixed raw and treated greywater, it is unclear to what extent the treatment system was fed with higher polluted greywater between the sampling times. For an increased stress test, the house should be inhabited permanently over a longer period. Over the experimental period, none of the parameters in the treated greywater showed a trend towards accumulation, one example being COD in Figure 2. This is in contrast to a previous study of the authors on a closed-loop laundry pilot facility with similar technology (Buehler et al., 2021), showing accumulation of COD, TOC and turbidity over time. Even if the two system are not directly comparable, accumulations in the KREIS-Haus should be further observed over a longer period, and if apparent, adequately managed. Assessment of the treated rainwater (drinking water) shows that the values for turbidity and TOC were at times above the limit values of the Swiss regulation for drinking water (TBDV, 2016) (Table 2). All other monitored parameters complied with the regulation. Over the experimental period, the house was operated 100% water self-sufficiently meaning that no external water supply other than rainwater was used. The overflow tank was emptied twice and contained an average of 50 mg/L COD. According to Swiss regulation, the water could have been discharged into a water body (limit value 60mg/L COD) (GSchV, 1998). However, it is unclear if compliance with regulation can be ensured with higher occupancy of the house. These first results indicate that the water concept in KREIS-Haus is a promising approach, but it's operation needs to be monitored over a longer period with higher occupancy.

Table 1. Mean and standard deviation of abiotic parameters before and after the treatment of rainwater and greywater. Removal rates after the rainwater and greywater treatment.

		Temp.	Turbidity	pH	EC	O_2	BOD_5	COD	TP	TN	TOC	Tensides cationic	Tensides anionic
		(°C)	(FNU)		(µS/cm)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Rainwater	Mean	18.6	4.0	6.4	24.9	6.1	n.m.	15.9	0.14	1.2	5.6	0.3	0.1
	Std.	2.7	2.6	0.3	6.7	2.6	n.m.	13.6	0.1	0.6	3.3	0.2	0.1
	n	10	16	17	17	17	n.m.	17	16	16	13	16	16
Treated rainwater	Mean	20.7	2.5	6.5	37.2	6.3	n.m.	12.3	0.1	0.7	3.3	0.1	0.1
	Std.	4.6	1.1	0.3	18.6	1.8	n.m.	10.8	0.1	0.3	2.1	0.1	0.1
	n	10	16	17	17	17	n.m.	17	16	15	15	16	16
	Removal		38%					23%	30%	40%	41%	44%	41%
Greywater	Mean	18.6	65.0	6.9	238.0	2.5	42.4	176.6	0.5	3.9	23.1	1.7	7.6
	Std.	3.4	42.3	0.2	41.5	2.6	33.6	96.8	0.3	1.9	7.7	0.6	5.9
	n	10	16	17	17	17	14	17	16	14	14	15	16
Treated greywater	Mean	18.2	1.2	7.3	258.6	6.0	5.3	13.9	0.4	2.2	6.7	0.4	0.2
	Std.	2.7	0.8	0.3	32.7	1.8	2.2	5.3	0.2	1.1	4.0	0.5	0.3
	n	10	16	17	17	17	11	17	15	16	16	16	16
	Removal		98%				87%	92%	18%	44%	71%	75%	97%

Table 2. Comparison of the treated rainwater with the limit values of the Swiss drinking water regulation.

	Turbidity	pH	EC	TP	TOC	Total aerobic count	E.coli	Enterococci	P.aeruginosa	Legionella
	(FNU)		(µS/cm)	(mg/L)	(mg/L)	CFU/ml	CFU/100ml	CFU/100ml	CFU/ml	CFU/L
Treated rainwater in KREIS-Haus	2.5	6.5	37.2	0.1	3.3	32	0	0	0	<20
Limit values:										
TBDV - Drinking water	1.0	6.5 - 9.5	2500.0	1.0	2.0	300	n.d.	n.d.	n.d.	1000
TBDV - Bathing water						1000	100	50	10	1000

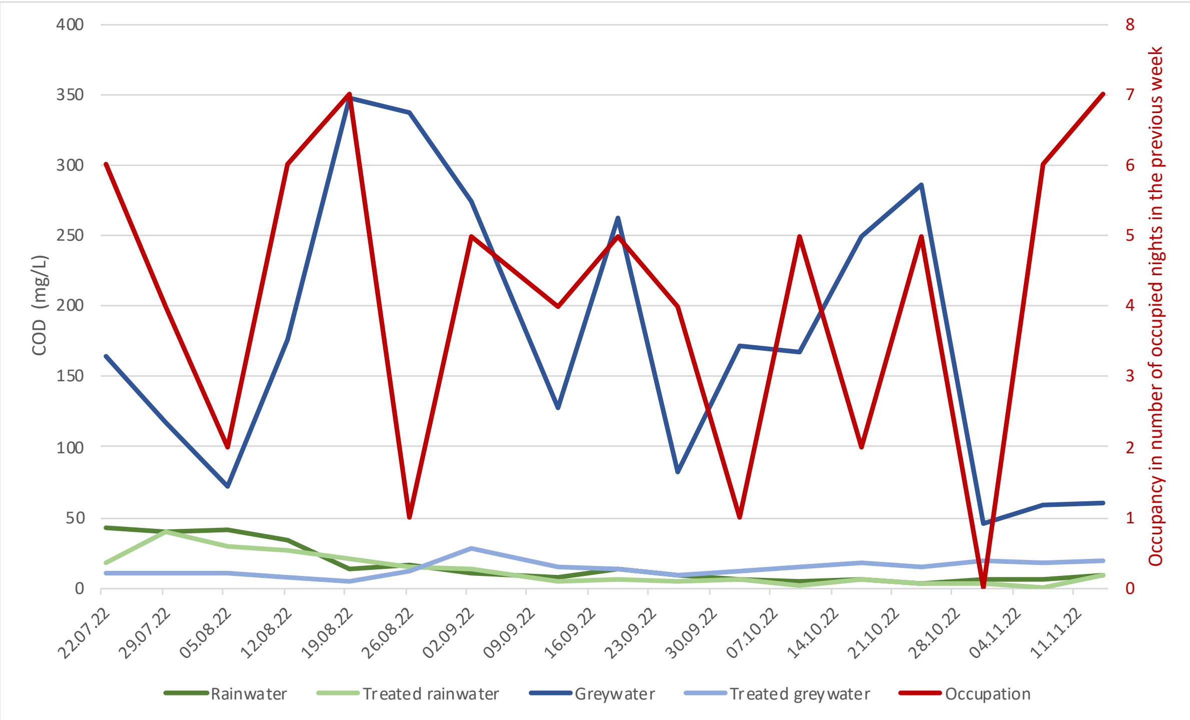

Figure 2. COD over the experimental period before and after the treatment of rainwater and greywater (primary y-axis) and occupancy of the house (secondary y-axis)

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