Circular Economy and Sustainability
https://doi.org/10.1007/s43615-021-00077-2

ORIGINAL PAPER

Towards Water and Energy Self-Sufficiency: a Closed-Loop, Solar-Driven, Low-Tech Laundry Pilot Facility (LaundReCycle) for the Reuse of Laundry Wastewater

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Received: 3 February 2021 / Accepted: 9 June 2021/Published online: 12 July 2021

Abstract

In the scope of this study, a pilot facility for the recycling of laundry effluent was developed and tested. With the aim to enable nearly complete energy and water self-sufficiency, the system is powered by a photovoltaic plant with second-life batteries, treats the wastewater within the unit and constantly reuses the treated wastewater for washing in a closed cycle. The technology for wastewater treatment is based on a low-tech approach consisting of a physical/mechanical pre-treatment and biological treatment in trickling filter columns. The treatment process is operated in batch mode for a capacity of five washing cycles per day. During five weeks of operation water quality, energy consumption and production, water losses and washing performance were monitored. The system recovered 69% of the used water for the washing machine while treating the wastewater to the necessary water quality levels. The average COD removal rate per cycle was 92%. Energy analysis was based on modelled data of the monitored energy consumption. With the current set-up, an internal consumption rate of 80% and self-sufficiency of 30% were modelled. Future developments aim at increasing water and energy self-sufficiency and optimizing the water treatment efficiency.

Keywords Greywater treatment · Wastewater reuse · Laundry wastewater · Biological wastewater treatment · Self-sufficiency · Off-grid solar power

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Introduction

Freshwater is becoming an increasingly scarce resource due to global trends such as urbanization, climate change and population growth [1]. Therefore, the 2017 United Nations Global Water Report [1] highlights the importance of wastewater reuse as a strategy to address water scarcity. Since decentralized water systems not only reduce water consumption, but also increase resiliency of the water infrastructure network and reduce the costs of infrastructure replacement, they are often more sustainable than centralized water systems [2]. The local treatment and reuse of greywater is experiencing increased popularity because greywater (water from kitchen, bath and washing machine) is only lightly polluted compared to average municipal wastewater [3]. A number of studies have examined local greywater treatment and its reuse potential [4–9]. The greywater is typically treated to a quality level where it can be reused for non-potable purposes with lower quality requirements such as irrigation or toilet flushing [10–14]. The cascading use of the treated greywater has the potential to reduce freshwater demand and wastewater discharge. However, such systems nevertheless require suitable infrastructure to supply the freshwater and discharge the wastewater.

Washing machines use approximately 50 L water per washing cycle and are considered one of the most significant contributors of pollutants to greywater [5, 15]. The reuse of laundry effluent could therefore be an important contribution to reduce the use of freshwater, as well as wastewater-associated problems such as pollution and eutrophication. Laundry effluent has different characteristics when compared to other greywater sources from bathroom and kitchen; for example, its chemical oxygen demand (COD) content is typically higher and more variable than for greywater from bathroom. Reported COD values in laundry effluent range between 58 and 4155 mg/l while for bathroom between 64 and 903 mg/l [13, 16–18]. The reported values for total suspended solids (TSS) in laundry wastewater range between 188 and 315 mg/l, which is higher than for bathroom (58–78 mg/l) but lower than for kitchen (134–625 mg/l) [13, 16, 17]. Since many countries have banned the use of phosphate for laundry detergents, total phosphorus (TP) is typically low in laundry greywater [4], as are nitrogen concentrations [18]. Some studies even supplemented laundry greywater with nitrogen in order to achieve an optimal nutrient ratio for water treatment [19, 20]. Mainly due to the alkalinity of most laundry detergents [21, 22], laundry wastewater typically has an alkaline pH [3, 13].

Due to high fibre and surfactant concentrations as well as high and varying COD concentrations, the design of technologies for treating and reusing laundry effluent needs to be adapted to the characteristics of laundry wastewater. Hoinkis and Panten [23] developed a membrane bioreactor (MBR) in combination with reverse osmosis (RO) from pilot to large scale. Guilbaud et al. [24] used a direct nanofiltration process with tubular membranes for potential laundry wastewater recycling in a ship. Other high-tech approaches that have been tested to treat laundry wastewater include bipolar electrocoagulation-electroflotation [25]; coagulation [26]; membrane filtration [26]; moving bed bioreactor (MBBR) [20]; ultrafiltration [27]; activated carbon filtration [28]; vibrating shaker screen and tubular filtration [29]; a combination of ozone, catalyst and cavitation [30]; and a combination of coagulation, flocculation, dissolved air floatation, sand filtration, ozonation and GAC filtration [31]. Most of these systems were developed for implementation in industrial environments and typically require high capital and operating cost. Only little attention has been given to the design of low-cost and low-tech solutions, one exemption being Ahmad and EL-Dessouky [32], who developed a low-cost treatment system for the laundry of a petroleum refinery in Pakistan. The treatment process was based on a sand and gravel filter with three layers. The treated water, however, was ranked as low-grade water and was found to be only suitable for reuse in the first rinse of the dirty clothes [32]. However, in particular, low-tech and low-cost systems can be a practical solution to treat and reuse laundry wastewater on domestic scale in under-resourced areas.

This study examines a pilot low-tech laundry facility on domestic scale where the laundry effluent is treated within the unit and repeatedly reused for washing in a closed cycle. The system is based on mechanical pre-treatment, followed by biological treatment in trickling filter columns. Potential issues arising from a closed-loop recycling system were investigated, such as pollutant removal efficiency of the treatment steps, energy and water self-sufficiency and washing performance.

Materials and Methods

Closed-Loop Pilot Laundry Facility

The closed-loop pilot laundry facility was configured as a semi-batch system in which a laundry machine (Schulthess Spirit 530, Wolfhausen, Switzerland) was connected to two treatment steps (mechanical pre-treatment and biological treatment) with their respective water reservoirs (Fig. 1). The water reservoirs consisted of four tanks (Faserplast, Logistikbox, PE, Rickenbach, Switzerland), each comprising 300 L: wastewater tank, filter water tank, treated water tank and rainwater tank. Within the wastewater, filter water and treated water tank, there

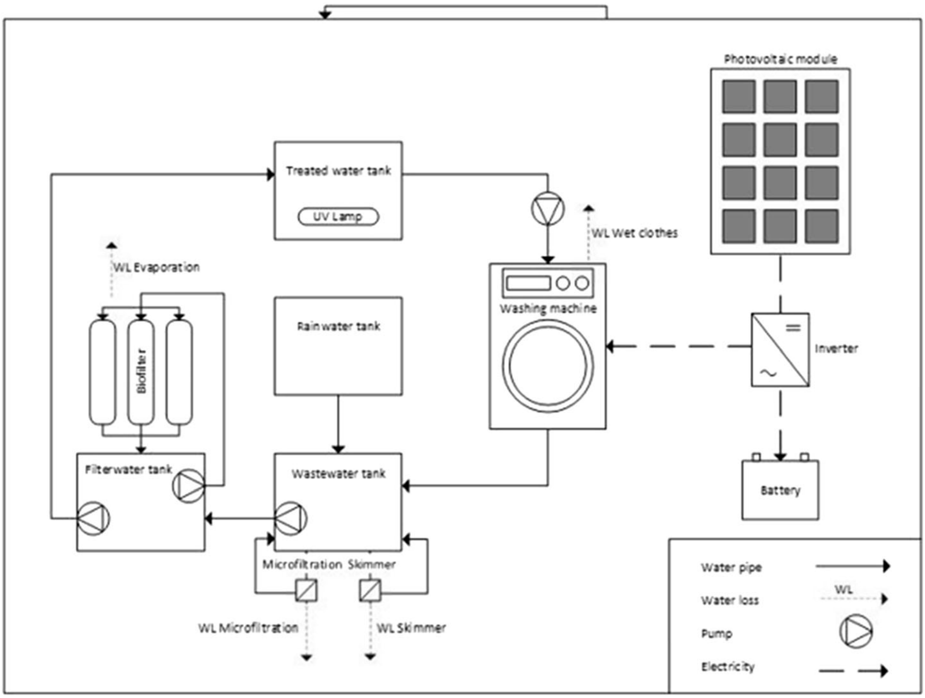


Fig. 1 Scheme of pilot facility for closed-loop recycling of laundry wastewater (LaundReCycle). The electricity of the photovoltaic plant is used for powering the washing machine as well as the pumps and filters of the treatment system

were two alternating batches. Each batch contained a maximum of five washing cycles (approximately 50 L per cycle). The laundry machine obtained the water via a booster pump (Gardena, Hauswasserwerk 3000/4 eco, Mägenwil, Switzerland) from the treated water tank. The laundry effluent was discharged into the wastewater tank, from where the total batch was pre-treated. The pre-treatment consisted of a micro filtration step (Astralpool NanoFiber auto 200, Barcelona, Spain, mesh size 5–8 μm) and a skimmer (Aqua Medic EVO 3000, Bissendorf, Germany) which run in parallel continuous circulation for a minimum of 19 h to treat the total batch of 5 wash cycles. The micro filtration eliminated fibres and particles, and the skimmer (Fig. 1: WL Micro filtration, WL Skimmer) removed excess detergent through small air bubbles which caused foaming, in order to prevent an overload of detergent to the biofilters. Subsequently, the entire pre-treated water was pumped from the wastewater tank to the filter water tank. Three biofilters (trickling filters/attached growth) in transparent columns (acrylic glass, self-made), each having a height of 100 cm, diameter of 25 cm and volume of 49 L and filled with 30 L filter media, were operated in parallel at an average flow rate of 400 l/h and removed the remaining particles, while the biofilm metabolized organic load (COD/BOD) and assimilated nutrients. The filter media was non-sterile and not seeded with any microorganisms. After a minimum treatment of 24 h, the batch was pumped into the treated water tank, from where it was reused for the next washing cycle. In this experiment, losses were refilled with rainwater from an external rainwater source (tap rainwater), directly fed into the treated water tank. The rainwater tank of the facility was not in use. The system design foresees that water losses can also be compensated by rainwater from the roof of the facility, which would be collected in the rainwater tank. Refill rainwater would be led into the wastewater tank, so that any contamination (pollen, solids) can be removed in the treatment process before water is reused for washing.

For the filter media in the trickling filter columns, a mix of perlite (Ricoter Erdaufbereitung AG, Switzerland, particle size 1–3 mm) and coco coir (ökohum GmbH, Switzerland) in proportion 3:1 (volume) was used. Prodanovic et al. [33] found that perlite, a medium with lower retention time, is mostly responsible for physico-chemical removal processes, while coco coir, a media with higher retention time, mostly enables biological removal processes. As a result, Prodanovic et al. [33] identified the combination of both as most suitable media for greywater treatment.

The pilot facility was powered by a 900 Wp photovoltaic power plant with 12 CIGS thin-film modules (Type SL1-75F, Solibro GmbH, Germany) on the roof, coupled with battery storage. The modules covered a total area of 8.8 m^2 and were installed at an angle of 10 degrees. For the batteries, reused second-life lithium-iron phosphate batteries (Type SE100AHA, Kyburz Switzerland AG) with a total of 4 kWh capacity were installed. For the inverter, a 5 kW on-grid InfiniSolar inverter (Voltronic Power, Taiwan) was used.

Pilot Operation

Prior to the experiment, the trickling filters were operated in a ramp up phase of three months with a total of 50 washing cycles to establish the biofilm of the biofilter. The experiment itself was carried out from 14/10/2019 to 15/11/2019, running four washing cycles per day on three consecutive days of the week (Tuesday to Thursday). As a result, the water of batch A was reused eight times and of batch B seven times over the total experimental period of five weeks. For the laundry, a standardized washing load was used. Each load comprised eleven 100%

cotton T-shirts (Clique, Codogno LO, Italy) resulting in approximately 1.4 kg of dry weight per cycle. The experiment started with newly purchased white, coloured and black T-shirts, which were used for the whole duration of the experiment. The four daily washing cycles followed a pre-set colour arrangement of the shirts. The first laundry was always white, the second and third coloured and the fourth black. A standard soiling solution of 10 ml, adapted after Gotoh [34] and Rojvouranun [35] (Table 1), was added to the second, third and fourth washing cycle in order to recreate soiled laundry. Since the white laundry was not soiled, this allowed to identify a potential discoloration of the white laundry due to a potential coloration of the recycled water. For all washing cycles, the express wash program of approximately 40 min at 40°C and 30 ml detergent Coop Oecoplan Flüssigwaschmittel Color Gel (Coop, Basel, Switzerland) were used. Table 2 shows the operating schedule of the first week of the experiment. This schedule was then repeated, as can be seen in the full operating schedule of the five-week experiment (Supplementary Information Table S1).

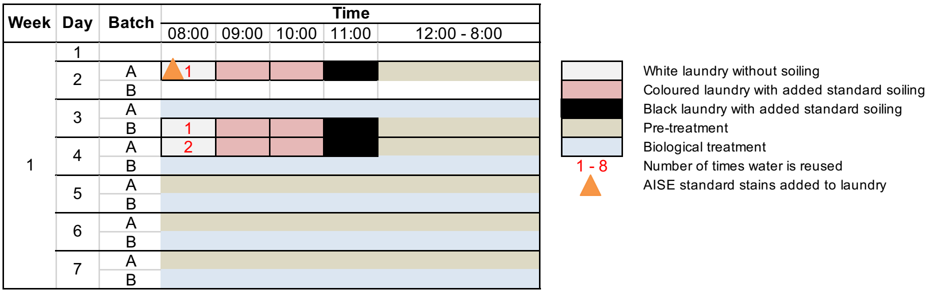
Sampling and Analytical Methods

On each washing day, seven water samples (50-ml tubes) from the different treatment steps (before and after water transfers, different batches A/B) were taken. Analyses of chemical oxygen demand COD (mg/l) and total phosphorus TP (mg/l) were performed with spectrophotometry (Hach, LCI400 for COD and LCK348 for TP); total nitrogen TN (mg/l) and total organic carbon TOC (mg/l) were measured with a TOC/TN Analyzer (TOC-L Series (Combustion), Shimadzu). Turbidity (FNU, ISO 7027), pH, dissolved oxygen DO (mg/l), electrical conductivity EC (μS/cm) and temperature (°C) were continuously logged with probes (Hach, Switzerland) in the wastewater, filter water and treated water tank. Furthermore, in each of these tanks, the water height (cm) was continuously logged with probes (Vega Messtechnik AG, Pfäffikon, Switzerland). To evaluate and ensure the cleaning performance of the detergent, once per week, three sets of AISE standard stains (AISE, Brussels, Belgium) were added to the white laundry and dried for a minimum of 24 h after washing. The washing performance was assessed with a camera-based multispectral colour measurement instrument (Mach 5, Colour Consult, the Netherlands). The energy consumption was monitored by the solar installation. Pathogens were not analysed, due to their unlikely or marginal presence in the type of wastewater used in the experiment. The exemplary sampling schedule of day 4 is shown in Table 3.

Table 1 Composition of standard soiling solution, adapted after Gotoh [34] and Rojvouranun [35]. Compounds for 1 L solution, of which 10 ml were used per washing cycle

Ingredients	Amount (per 1 L tap water)
Vegetable oil	5 ml
Apple cider vinegar	5 ml
Salt	5 g
Cornstarch	5 g
Soil	5 g
Charcoal	5 g
Detergent (emulsifier)	5 ml

Table 2 Operating schedule of week 1 of the five-week experiment



Data Analysis

Removal rates are calculated according to Eq. 1, where W_{raw} and W_{treat} denote mean concentrations of investigated substances in the raw wastewater and in the effluent of the treatment steps, respectively.

$$Removal\ [\%] = 100 - \frac{100 * W_{treat}}{W_{raw}} \tag{1}$$

Energy analysis was based on modelled data of the monitored energy consumption of a standard washing day. The values of the monitored energy consumption were imported into the software Polysun (Vela Solaris AG, Winterthur, Switzerland). Polysun was used to model the following values and performance indicators: annual solar production AC (kWh), total annual consumption (kWh), self-consumption (%) and self-sufficiency (%). The self-consumption is the self-consumed part of the solar production relative to the total solar production [36]. It indicates to what degree the produced solar energy can be directly consumed by the system. The self-sufficiency is the self-consumed part of the solar production relative to the total consumption of the system. It indicates to what degree the on-site generation is sufficient to cover the total energy demand of the system [36]. The values were modelled for the current configuration and operation of the system, as well as for optimized scenarios. As a realistic scenario, four washing days per week, with four washings per washing day, were assumed.

Table 3 Sampling schedule on day 4 of the experiment

Daily schedule (example day 4)	07:55	08:00	08:05	08:10	08:20	13:00	17:00
Sample biofilter	A* 1**						
Transfer biofilter ➔ freshwater		A 1 ➔ A 2**					
Sample freshwater			A 2				
Sample wastewater			B* 1				
Transfer wastewater ➔ biofilter				B 1			
4 washing cycles					A 2		
Sample wastewater						A 2	
Sample biofilter						B 1	
Sample wastewater							A 2
Sample biofilter							B 1

*A / B: Name of the two alternating batches; **1 / 2: Number of times water is reused

The water balance was calculated based on the monitored water levels. The water volume was calculated from the water levels and the tank size (length, 93 cm; width, 59 cm). The respective differences in water levels indicated the water losses.

To evaluate the washing performance, the method of AISE [37] was used. The method is based on the y-values of the colour coordinates. One performance test was based on three sets of stains, where each stain was measured twice. For each stain, the mean value of all measurements was calculated. To calculate the overall washing performance, the mean values of all 14 stains were summed up.

Results

Pollutant Removal

Water quality parameters were monitored in the laundry effluent, after pre-treatment, after the biofilter and in the treated water. The treated water was composed of the filter water from the biofilter, mixed with refill tap rainwater to compensate for the water losses. The mean water temperature in the system ranged from 13.1°C after the pre-treatment up to 16.4°C after the biofilter (Table 4). The system achieved an overall COD removal of 91%, with the largest removal (72%) due to the pre-treatment (Table 4). The treated water reached a final average value for COD of 28.3 mg/l (Table 4). Turbidity was reduced by a total of 75% (58% in pre-treatment) reaching a final mean value of 5.4 FNU. Nutrient concentrations were very low but for TN still above the limit of detection. With repeated reuse of the treated water, COD, TOC and turbidity in the treated water tank gradually increased over the five weeks (Fig. 2). At the end of the experiment, there was a rather sharp increase in concentrations, which coincided with a water temperature drop to 8.6 °C due to cold weather.

Energy Analysis (Model Based)

With the described design and operation at the location in Wädenswil, Switzerland, the model calculated a self-consumption of 80% and self-sufficiency of 30% (Table 5). Most of the

Table 4 Mean and standard deviation of abiotic parameters in the different treatment steps and their removal percentages after pre-treatment and after total treatment during the five weeks experimental period

Parameter	Unit	Input water, recycled*	Laundry effluent	After pre-treatment		After biofilter	
		(n = 14)	(n = 14)	(n = 14)	(%)	(n = 15)	(%)**
COD	mg/l	19.5 ± 10.9	318.4 ± 40.7	88.9 ± 45.2	72	28.3 ± 16.4	91
TOC	mg/l	7.5 ± 4.7	55.2 ± 16.9	21.4 ± 8.8	61	11.0 ± 5.5	80
TN	mg/l	0.4 ± 0.2	0.7 ± 0.5	0.3 ± 0.1	57	0.2 ± 0.03	71
TP	mg/l	< 0.03	< 0.03	< 0.03	-	< 0.03	-
Turbidity	FNU	1.2 ± 2.3	21.5 ± 5.6	9.1 ± 4.5	58	5.4 ± 1.8	75
pH		6.9 ± 0.1	6.9 ± 0.1	6.9 ± 0.06	/	6.9 ± 0.0	/
EC	µS/cm	380.7 ± 45.8	464.5 ± 30.1	341 ± 88.2	/	437.9 ± 72.7	/
DO	mg/l	11.3 ± 1.1	9.69 ± 3.3	10.84 ±0.9	/	9.1 ± 1.6	/
Temp	°C	13.4 ± 2.1	15.9 ± 4.7	13.1 ± 3.7	/	16.4 ± 1.4	/

*Treated water after biofilter mixed with tap rainwater from refill, measured in the treated water tank**Cumulative removal percentage of both treatment steps

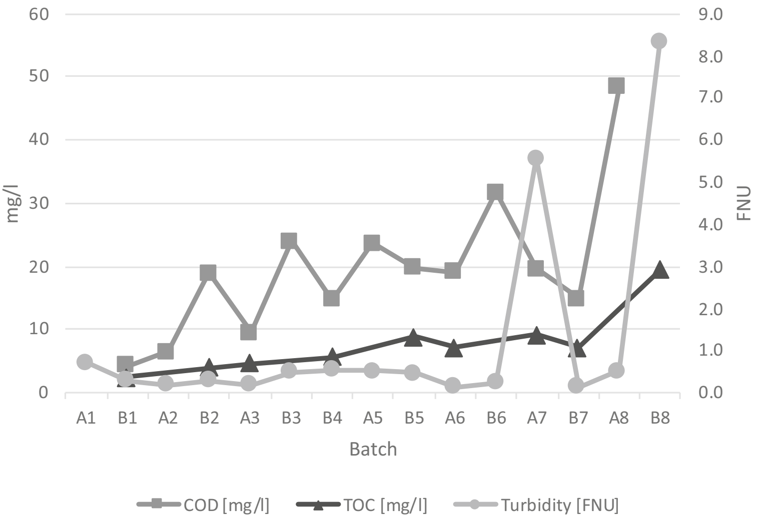


Fig. 2 Development of COD/TOC concentrations and turbidity in two alternating batches (A/B) over the experimental period of 5 weeks in the treated water tank

energy (78%) was used by the pumps and filters for the water treatment, since these were continuously running. Also, the PV module area was rather undersized for this installation. Therefore, a set of optimization measures were implemented into the software. These included the following: intermittent pump/filter operation, double the size of the module area and time of washing at midday instead of morning. By implementing these measures at the location in Switzerland, self-sufficiency could be increased to 66% (Table 5). Since the target market for the LaundReCycle is in arid regions with water scarcity, the simulation was also performed for Cape Town, South Africa. In South Africa, the solar radiation is 66% higher than in Switzerland. In combination with all optimization measures, self-sufficiency of 86% could be achieved.

Water Balance

The analysis of the water balance over the duration of the whole experiment showed that 69% of the used freshwater entering the washing machine was reused at the end of the treatment.

Table 5 Modelled performance for one year based on monitored data, and optimized scenarios in Switzerland and South Africa

Performance indicator	Pilot configuration, Switzerland	Optimized configuration, Switzerland	Optimized configuration, South Africa
Annual solar production AC	1002 kWh	1722 kWh	2438 kWh
Total annual consumption	2706 kWh	1579 kWh	1542 kWh
Annual consumption washing machine	605 kWh	605 kWh	605 kWh
Annual consumption water treatment	2102 kWh	974 kWh	937 kWh
Self-consumption	80 %	58 %	53 %
Self-sufficiency	30 %	66 %	86 %

The largest fraction (26%) was lost in the pre-treatment, and specifically in the skimmer, while evaporation losses (2%) and withdrawal of wet clothes (3%) played a minor role. These calculations do not include the use of rainwater from the roof of the facility, which could significantly improve the overall water balance. In this case, the collection of rainwater would be regarded as a gain inside the system boundary, as defined by Buehler et al. [38].

Washing Performance

The mean cumulative AISE washing performance was 808 with a standard deviation of 11. Thus, the washing performance was subject to rather large fluctuations, while no major deviations on the individual stains were observed. There was no clear trend towards better or worse washing performance over the five-week period. High performance washing detergents typically achieve AISE values of 1000 and higher. However, in this experiment, other washing settings were applied; therefore, the results are not comparable to other washing tests but only within themselves.

Discussion

The pilot operation of the LaundReCycle showed that the low-tech design achieved COD removal comparable to other studies (Table 6). Typical high-tech approaches achieve COD removal between 87 and 99 %. The 91% COD removal of the low-tech approach in this study lies in the range of the high-tech approaches. In comparison, Ahmad and EL-Dessouky [32] did not achieve any COD removal with the low-tech sand and gravel filter. However, removal of turbidity in this study (75%) was in the range of Ahmad and EL-Dessouky [32] (Table 6). Since nutrient concentrations in the laundry effluent were very low (0.7 mg/l TN, < 0.03 mg/l TP), comparison of removal rates is likely not expressive. Other studies report values from 2.8 to 40 mg/l for TN and 0.2 to 51.6 mg/l for TP [13, 17, 18, 23]. The pH of 6.9 was almost neutral. This is in contrast to predominantly alkaline pH values between 7.5 and 11 [13, 16–20, 23, 25, 26, 32, 39–42]. Some studies, however, also reported nearly neutral pH values between 7 and 7.2 [24, 31], and some even acidic pH between 3.3 and 6.8 [18, 43], possibly due to relatively high concentrations of organic acids [18]. The rather neutral pH of this study could be a result of the use of rainwater or a certain composition of the detergent. Laundry effluent typically has high variations in COD [18]. The COD concentration (318 mg/l) was in the same range of studies with lightly polluted laundry effluent (Table 6) [26, 32]. However, most studies report higher COD values between 582 and 1700 mg/l (Table 6) [19, 20, 23, 24, 31, 44]. The same pattern can be seen for TOC and turbidity. The laundry effluent of this study can therefore be classified as lightly polluted. Hence, to better test the treatment performance of the facility, it is necessary to increase soiling of the laundry by adapting the standard soiling solution in Table 1.

So far, no other study used biological trickling filters for the treatment of laundry effluent. According to Zhang et al. [45], natural ventilation trickling filters for the treatment of municipal wastewater have been receiving increased attention in recent years. Trickling filters do not require any active aeration or sophisticated equipment, and therefore have the potential to achieve high treatment efficiency while keeping operating and capital costs low [45, 46]. Chang et al. [47] underline that attached biofilm growth on a filter media allows for higher concentrations of active biomass than in suspended growth activated sludge systems, which

Table 6 Comparison of pollutant removal of technologies for treatment of laundry effluent

Study	Technology	COD			Turbidity			TSS			TN			TP		
		WW (mg/l)	TW (mg/l)	R	WW	TW	R	WW (mg/l)	TW (mg/l)	R	WW (mg/l)	TW (mg/l)	R	WW (mg/l)	TW (mg/l)	R
[32]	Sand and gravel filter with three layers	310	310	0%	10.3	2.4	77%	380	40	89%						
[19]	Membrane bioreactor	1700	1700	97%							8.6*	30.5*	-253%	34*	35*	-3%
[20]	Moving bed bioreactor (MBBR)	836*	836*	92%				143*			9.7*			11.8*		
[31]	Combination of coagulation, flocculation, dissolved air floatation, sand filtration, ozonation and GAC filtration	602	602	87%	110	0.8	99%	166	2.5	98%				1.9	-	
[25]	Bipolar electrocoagulation-electroflotation coagulation	582*	582*	93%	362*	8*	98%									
[24]	Direct nanofiltration with tubular membranes	1340	1340	> 98%	120			78								
[23]	Membrane bioreactor (MBR) with reverse osmosis (RO)	1050	1050	94%							40	2	95%			
[26]	Coagulation and active carbon	280	280	93%				35	< 5		2.8	2.6	5%	9.9	1	90%
[26]	Membrane filtration	280	280	99%				35	8		2.8	0.03	99%	9.9	0.14	99%
This study	Solids filter, skimmer and biofilter	318	318	91%	21.5	5.4	75%				0.7	0.2	71%	< 0.03	< 0.03	

*Calculated mean

WW wastewater, *TW* treated water, *R* removal allows reducing the size of the reactor. Moreover, the filter medium can act as an additional physical filter by adsorption [47]. In fact, it is unclear to what extent the biofilter performance in this study is based on biological or physical treatment processes. During the ramp up phase, considerable COD removal was already observed after the first cycle (data not shown), before any biofilm could have been established. To optimize the system design and the biofilter in particular, further investigations on the physical processes (adsorption isotherms) and microbial communities in the biofilter are needed. Since biofilms widely occur in the washing machines themselves, Gattlen et al. [44] suggest using these microbial communities for the wastewater treatment, as these have already adapted to the chemical and mechanical pollution in laundry effluent. On the other hand, Jabornig and Favero [7] show that prior inoculation with microorganisms has no influence on the biofilm build-up time.

Treating laundry effluent with biological processes is in particular challenging regarding the wide variation of nutrient concentration of laundry wastewater [10, 17]. Nutrient concentrations mainly depend on the type and amount of soiling on the laundry, ranging from only lightly stained clothes to heavily polluted laundry from industrial environments. Both extremes can pose a risk to the biofilter. Too low nutrient concentrations can lead to an undersupply of the biofilter, resulting in a reduced treatment performance [48]. On the other hand, too high nutrient concentrations might exceed the treatment capacity of the biofilter. Should undersupply of nutrient limit the performance of the biofilter, nutrients could be added to the biofilter as this has been done with nitrogen in other studies [19, 20].

The development of COD, TOC and turbidity over the duration of the experiment (Fig. 2) indicated a gradual increase of these parameters with a considerable leap in the last batch. Possible explanations could be the temperature drop inhibiting biological processes, clogging of the micro filtration, the saturation of the biofilter due to COD adsorption, given that the process is present, or sloughing of the biofilter. However, due to the near absence of phosphorous TP (Table 4), biofilm growth could have been limited as a result of nutrient undersupply. Nevertheless, biological processes could have still taken place due to potentially leaking nutrients from coco coir. Should future long-term operation lead to sloughing of the biofilter, a removal system, such as a settler, would need to be installed.

The aim of the LaundReCycle is to operate as a water and energy self-sufficient closed-loop system. An important aspect of closed-loop systems is the potential of accumulating substances. Accumulations have been observed in other closed-loop systems such as recirculating aquaculture systems [49] or in hydroponics [50], where nitrate respectively salt typically accumulate over time. In the scope of this study, the treated laundry effluent was repeatedly reused for the next washing. As a result, the two batches were recycled seven and eight times respectively. The average concentration for COD in the treated water was 28 mg/l. This value was always below defined limit values for laundry water from literature (50 mg/l [3], 100 mg/l [31], 150 mg/l [23]) but showed an increase over time. In addition, water losses were rather high (31%), meaning the same amount was refilled with tap rainwater, resulting in dilution of pollutant concentrations and lower values in the treated water. This illustrates that the level of water self-sufficiency has a counteractive effect on the pollutant concentration in the treated water. While future developments should aim to reduce water losses and increase recovery, special attention should be drawn to the investigation sufficient pollutant removal and potential accumulations over time. Such accumulations will likely be managed by exchanging part of the water, same as this is done in most circulating water systems. Another possible measure might be the use of non-ionic surfactants, regarding ions, combined with a well-adapted microbial flora in the biofilter to reduce the extent of required water exchange.

Furthermore, hygiene is an important factor when it comes to water reuse. Dolnicar et al. [51] have identified health concerns as one of the main factors when it comes to acceptability of water reuse. The design of the LaundReCycle incorporates a UV lamp for disinfection of the treated wastewater. However, in this study, the UV lamp was not yet included, because due to the type of soiling used in the experiment, the presence of coliforms was very unlikely. Therefore, the monitoring of hygiene parameters and the effectiveness of the UV lamp need to be studied. To achieve representative pathogen loads in the wastewater, the standard soiling solution needs to be adapted accordingly. Moreover, it should be taken into account that the UV lamp will increase the energy consumption.

Energy self-sufficiency could be optimized by implementing the proposed optimization measures. Further optimization measures include cold washing, if accepted by the user, turning off water treatment pumps once treatment goal is achieved, use more efficient pumps and use of eco washing program if longer washing times are acceptable. Furthermore, the used detergent is a crucial element. The faster and better its biodegradability, the higher pollutant removal can be achieved. Water self-sufficiency could be optimized by using rainwater from the roof of the facility and recovering losses. Particularly, the losses of the skimmer could either be reclaimed or the skimmer could be turned off completely and only used as back-up filter should the load on the biofilter be too high. Green walls for wastewater treatment [9, 33, 52, 53] could be used to treat the by-products from the skimmer and the filters and potentially reclaim these water losses. By implementing these measures, it is feasible that the system could be operated completely water and energy self-sufficiently, depending on the rainfall and solar radiation of the respective location.

Conclusion

In the scope of this study, the pilot facility for the recycling of laundry effluent (LaundReCycle) was operated and monitored during five weeks. The experimental design allowed to analyse a range of parameters in order to gain first insights into the performance and feasibility of the facility. Even though sufficient removal rates were achieved, a detailed understanding of the functionality of the biofilter is still missing. In order to achieve complete energy and water self-sufficiency while fulfilling hygiene requirements and sufficient pollutant removal, the system needs to be further optimized and evaluated, especially in regard to crucial parameters such as pathogens and accumulations over time. To better test the performance of the system, it is necessary to adapt the standard soiling solution to achieve representative pollution levels of the laundry effluent. The final aim is to implement the LaundReCycle in water-scarce and under-resourced areas. In this context, the next step should be to test the system under real-life conditions in terms of technical performance regarding the local climate conditions, as well as economic feasibility and social integration.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s43615-021-00077-2.

Availability of Data and Material Not applicable.

Code Availability Not applicable.

Author Contribution Conception and design were performed by Devi Buehler, Nadine Antenen, Matthias Frei, Ranka Junge, Christoph Koller and Andreas Schoenborn. Material preparation, data collection and analysis were performed by Devi Buehler, Nadine Antenen and Christoph Koller. The first draft of the manuscript was written by Devi Buehler. Nadine Antenen, Ranka Junge, Diederik Rousseau and Andreas Schönborn commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open Access funding provided by ZHAW Zürcher Hochschule für Angewandte Wissenschaften. The study was funded by seed-funding from Zurich University of Applied Sciences.

Declarations

Ethics Approval No approval of research ethics committees was required to accomplish the goals of this study.

Consent to Participate Informed consent was obtained from all individual participants included in the study.

Consent for Publication Informed consent was obtained from all individual participants included in the study.

Conflict of Interest The authors declare no competing interests.

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