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Treatment of greywater with nanofiltration for nutrient removal – 2-year experience from Helsingborg

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ABSTRACT

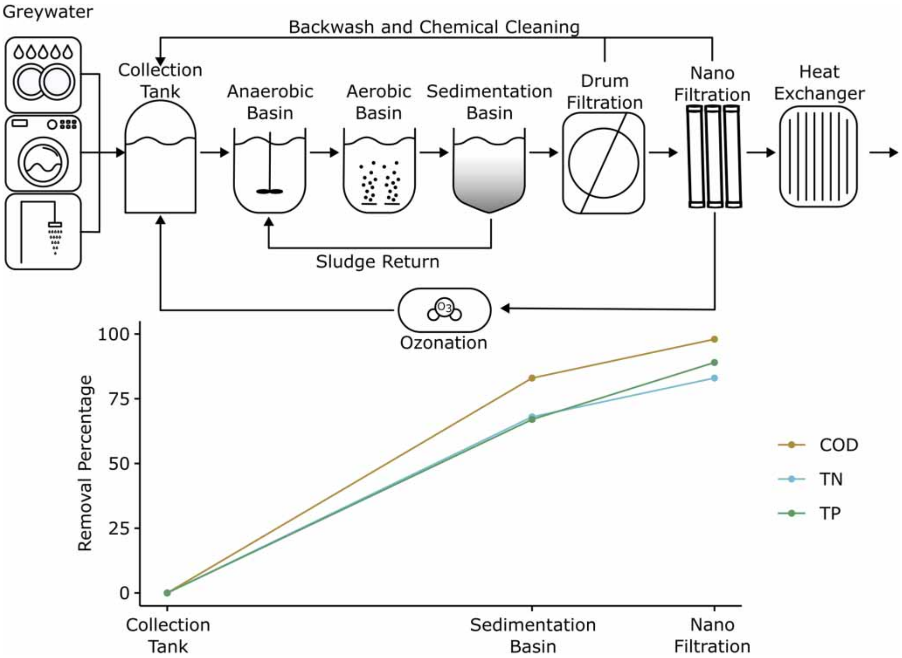
Source-separated sanitation and greywater treatment have become an increasingly attractive alternative to traditional wastewater management systems in recent years due to their potential to combat water scarcity, ease resource recovery, and meet tightening effluent demands. In Helsingborg, Sweden, source-separated wastewater from the new city district of Oceanhamnen is being collected and treated in a new treatment plant (RecoLab) to test, among other issues, how efficient greywater treatment can be in achieving low discharge limits for pollutants. The greywater treatment consists of activated sludge treatment, drum filter micro-sieving, and nanofiltration. In the first two years of operation, the robustness of the treatment system during periods with extreme conditions, e.g., very low and very high organic matter concentrations, was tested. The combination of biological treatment and nanofiltration has achieved stable effluent concentrations below 10 mg/L chemical oxygen demand, 2 mg/L total nitrogen, and 0.2 mg/L total phosphorus as average values for 22 months of operation with an average flow of 43 m^3/day. The treatment system for greywater treatment thus shows the possibility to achieve low discharge limits and meet the new proposed effluent demands of the EU Urban Wastewater Treatment Directive.

Key words: case study, greywater, nanofiltration, source-separated sanitation

HIGHLIGHTS

- Effluent greywater concentrations below 10 mg/L chemical oxygen demand, 2 mg/L N-tot, and 0.2 mg/L P-tot can be achieved without chemical precipitation.
- Nitrogen speciation in greywater indicates a relatively large portion of organically bound nitrogen.
- A 10 μm drum filter is adequate pretreatment for nanofiltration.

GRAPHICAL ABSTRACT



INTRODUCTION

Greywater treatment and the use of source-separated sanitation have been implemented across the world to combat increased demand and dwindling supplies of safe water through the reuse of the relatively dilute greywater stream from showers, baths, sinks, laundry, and dishwashers compared to traditional mixed wastewater (Sharma *et al.* 2013). In addition, source-separated wastewater allows for the recovery of resources in the form of heat from the greywater as well as nutrients and biogas from the more concentrated blackwater stream. Source-separated sanitation is not limited to water-stressed areas. As urban centers expand, source separation at the local scale is an alternative to increasing treatment plants' size and expanding capacity in the centralized sewer network. The proposed revisions to the EU urban wastewater treatment directive or UWWTD (Procedure 2022/0345 (COD)) put new restrictions that lower the permissible effluent concentrations of organic carbon, nitrogen, phosphorus, suspended solids, and micropollutants in wastewater treatment plant effluent. They are summarized in Table 1. These stringent demands will require more extensive treatment in conventional wastewater treatment systems. A possible way to achieve such stringent demands is the use of decentralized source-separated sanitation with the diversion of blackwater (using vacuum toilets) away from greywater as opposed to renovating existing infrastructure to add additional treatment steps and increase treatment capacity, which is a growing trend in Europe (Skambraks *et al.* 2017). This allows for the possibility of treating a more dilute greywater stream onsite with simpler technology due to lower influent concentrations while the smaller fraction of concentrated blackwater can be treated with more complex techniques on site or in central treatment centers.

While quite a few source-separated sanitation systems exist and some systems have been operating since the 1990s (Fittschen & Niemczynowicz 1997; Jenssen & Vråle 2003), most systems are limited to individual household or small neighborhood scales serving under 350 person equivalents (PE) (Boyjoo *et al.* 2013). A life cycle analysis (LCA) of constructed wetland and membrane bioreactor based decentralized wastewater treatment facilities at varying degrees of decentralization found that smaller scale systems generated more beneficial impact on global warming potential, eutrophication potential, and human health carcinogenic potential than larger scale systems (Kobayashi *et al.* 2020). However, the study also found that the added requirement of an additional pipe and pumps to return water for reuse at too large a scale added complexity to systems and lowered the overall positive impact of source separation. It was found that community scale systems of around 3500 PE had the largest net positive impact across all parameters, even when water reuse was not considered. This was supported by Lakho *et al.* (2022) who showed via LCA that the distance wastewater is transported is a major factor in calculating the environmental impact of these decentralized systems due to the energy required to pump wastewater over

Table 1 | Influent greywater characteristics with operational anomalies (Figure 3) removed

	Influent (mg/L)	Sedimentation (mg/L)	Nanofiltration (mg/L)	UWWTD (Procedure 2022/0345 (COD)) (mg/L)	Current environmental permit (mg/L)
COD	530 ± 397 $n = 81$	90 ± 86 $n = 80$	9 ± 14 $n = 48$	125	–
BOD_7	238 ± 55 $n = 116$	–	–	25	10
TSS	143 ± 39 $n = 78$	18 ± 16 $n = 77$	–	35	–
VSS	140 ± 50 $n = 73$	24^a ± 19 $n = 71$	–	–	–
TN	15.4 ± 8.7 $n = 81$	4.9 ± 4.5 $n = 80$	2.6 ± 2.4 $n = 51$	6	10
NH_4-N	3.65 ± 2.95 $n = 78$	0.25 ± 0.3 $n = 78$	0.11 ± 0.15 $n = 53$	–	–
NO_3-N	0.7 ± 0.28 $n = 17$	0.4 ± 0.35 $n = 82$	0.77 ± 1.2 $n = 52$	–	–
TP	1.99 ± 1.31 $n = 82$	0.65 ± 0.62 $n = 82$	0.21 ± 0.21 $n = 52$	0.5	0.5
PO_4-P	0.53 ± 0.44 $n = 82$	0.24 ± 0.39 $n = 78$	0.17 ± 0.2 $n = 52$	–	–
pH	7.2 ± 0.3 $n = 82$	7.2 ± 0.2 $n = 81$	7.8 ± 0.3 $n = 53$	–	–

[a] Method limitations based on filter weight lost in ignition.

n = number of samples taken within time period; UWWTD, the EU Urban Wastewater Treatment Directive.

Low suspended solids concentrations after nanofiltration led to the discontinuation of TSS and VSS measurement in nanofilter permeate, accounting for low n.

long distances. Lakho *et al.* (2022) noted that this LCA was based on conditions in the relatively flat Netherlands, and therefore, fuel sources for pump stations and the degree of gravity-driven sewers could likely change the predicted outcomes.

When the city of Helsingborg in southern Sweden decided to redevelop an industrial harbor with sustainability in mind, energy neutrality was a main goal of the renovation and source-separated sanitation with the potential for heat recovery and increased biogas production became a key component of achieving this goal (Schelbert *et al.* 2023). Wastewater that is generated in the redeveloped city district, called Oceanhamnen, is treated in an experimental wastewater recovery center called RecoLab. The city district uses the 'three pipes out' approach to source-separated wastewater with the entire system operating as pressurized sewers. Wastewater from vacuum toilets is collected as blackwater, food grinders installed on one side of the kitchen sink collect food waste, and the remaining domestic wastewater from showers, sinks, laundry, and the other side of the kitchen sink make up greywater. Oceanhamnen lies about 500 m from RecoLab and is composed of homes, offices, restaurants, hotels, beauty salons, and a school. Currently, source-separated wastewater from 1000 PE (based on the influent BOD_7 load in the greywater flow) or 65 m^3/d flow into RecoLab and once Oceanhamnen is completed, the treatment plant will eventually treat an inflow of 210 m^3/d.

Greywater, like traditional wastewater, can vary heavily in composition based on many factors, namely, location, culture, and legislation (Eriksson *et al.* 2002; Jefferson *et al.* 2004; Sievers *et al.* 2014). Sievers *et al.* (2014) also show that while there are still quite large variations in greywater composition from one site, that variability is substantially smaller than is seen in a survey of existing literature. Since greywater differs by definition from traditional wastewater, so does the nutrient composition (Jönsson *et al.* 2005). Jefferson *et al.* (2004) characterized greywater produced in the United Kingdom and found that it was deficient in nitrogen and phosphorus compared to the accepted optimum ratio of 100:5:1 C:N:P for conventional aerated activated sludge treatment and had a biodegradability more like that of tertiary effluent based on the forms in which nutrients are present. However, according to Li *et al.* (2009), greywater can have a biochemical oxygen demand (BOD)-to-chemical oxygen demand (COD) ratio similar to that of influent mixed wastewater, indicating relatively good biodegradability.

The context-based variability of greywater composition and nutrient concentrations as illustrated by Boyjoo *et al.* (2013), Ghaitidak & Yadav (2013) and De Gisi *et al.* (2016) results in a high degree of uncertainty on what effluent concentrations can be achieved (through widely applicable greywater treatment techniques). In addition, there is little practical knowledge reported on such a system on a large scale. Thus, the aim of this article is to evaluate what effluent concentrations can be achieved via biological and mechanical treatment of greywater and if they align with current wastewater effluent regulations.

METHODS

Site description

Greywater at RecoLab was treated in a multistep process, as shown in Figure 1. It first entered a collection tank ($80\ \mathrm{m}^3$) before being pumped into a biological treatment stage that consisted of an anaerobic basin (hydraulic retention time (HRT) $= 1.9 \pm 0.5$ h) followed by an aerobic basin (HRT $= 23 \pm 7$ h) intended to encourage enhanced biological phosphorus removal (EBPR). Both the anaerobic and aerobic basin are divided into two sections with 1/3 of the volume in one section and 2/3 of the volume in another to progressively expand the capacity of the greywater treatment line as the influent flow increases. The smaller 1/3 capacity basins were used until March 2022, when they were switched over to the 2/3 capacity basins. This and other operational events can be seen in the timeline in Figure 2.

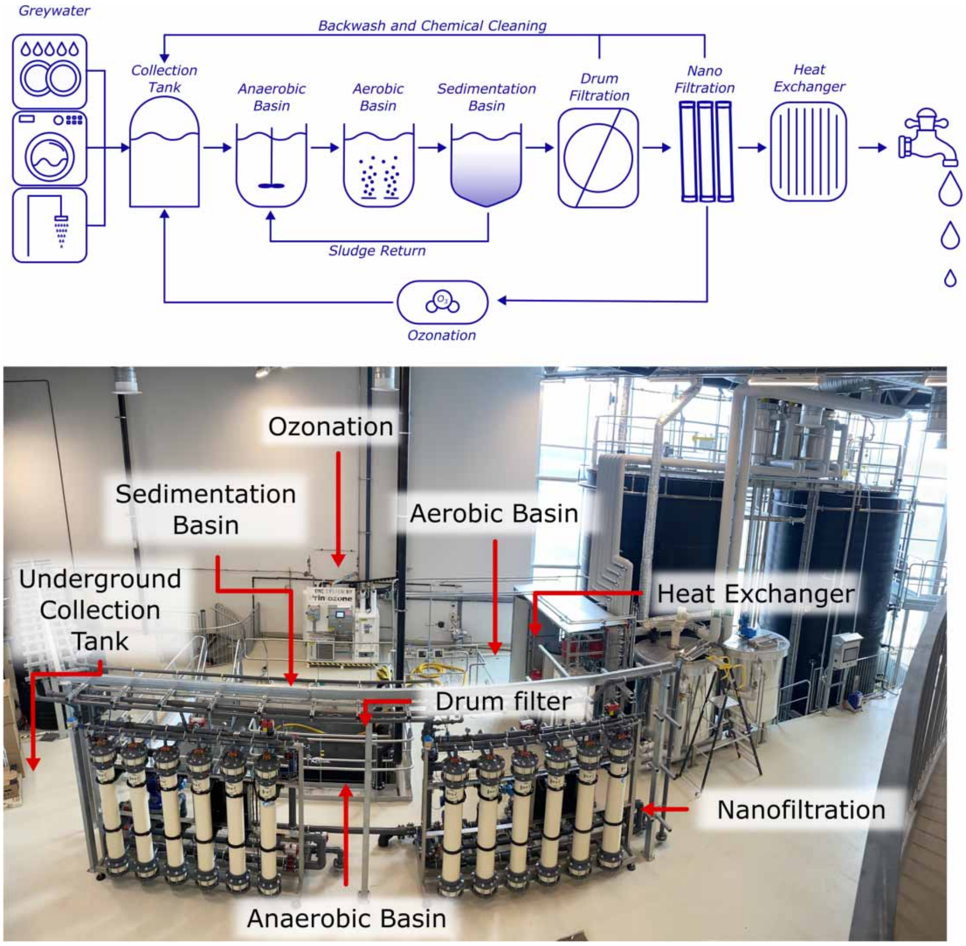


Figure 1 | Greywater treatment process.

Aerobic treatment was followed by a sedimentation tank (solids loading rate average of $11.1 \pm 8.8\ \mathrm{kg/m^2} \times \mathrm{d}$ and surface loading rate average of $0.15 \pm 0.05\ \mathrm{m^3/m^2} \times \mathrm{h}$) with sludge return from the sedimentation tank to the beginning of the anaerobic zone. Sludge return was operated on a set schedule, intermittently, and without flow measurement. Consequently, the sludge age was not monitored. Wasted sludge was sent to sludge handling at the main wastewater treatment plant in which RecoLab is housed.

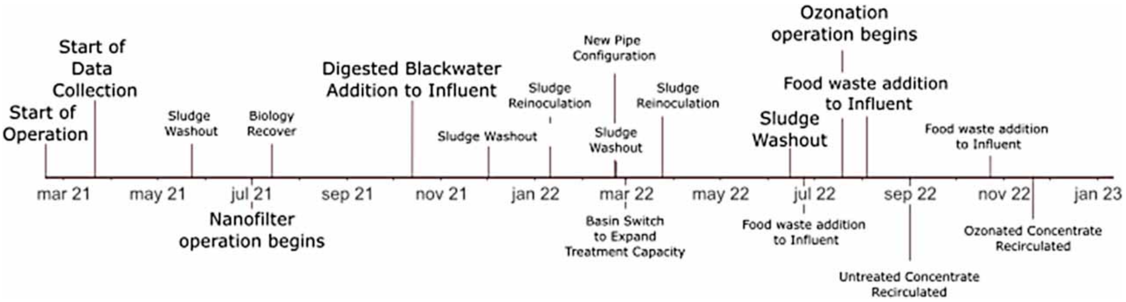


Figure 2 | Timeline of events with major events highlighted.

After the sedimentation tank, greywater passed through a 10 μm drum filter (Hydrotech, Vellinge, SE) before passing through nanofiltration (NX filtration dNF40, 400 Da molecular weight cutoff). Concentrate from the nanofilters was directed to an ozonation tank (Primozone, Löddeköpinge, SE) where ozone was added using a static mixer to break down pharmaceutical residuals before being recirculated to the collection tank to pass through the treatment again. Nanofilter permeate was then passed through a heat exchanger within the treatment facility, and the residual heat was used to preheat blackwater and food waste before anaerobic digestors. After the heat exchangers, greywater treatment was complete.

Figure 2 shows a timeline of operational events that occurred at the greywater treatment line at RecoLab. The biological treatment stage opened in February 2021 with nanofiltration being added in July 2021 and ozonation in July 2022. Recirculation of untreated nanofilter concentrate began at the end of August 2022, and ozonated concentrate from November 2022. The treatment process was designed across two procurements: the biology for nutrient removal and nanofiltration/ozonation for micropollutant removal. The treatment process was fed semi-continuously with the water level in the collection tank controlling when greywater was pumped into the system.

Greywater treatment functioned continuously, apart from a few periods where the drum filter stopped running and a buildup of greywater in the collection tank forced high flow rates through the activated sludge basins, causing sludge washout. Estimates of sludge age during the initial phases of operation indicate a sludge age close to 15 days. Ongoing experimentation is being completed to determine the optimum sludge age at this time. Currently, drum filters are backwashed after every treatment cycle, or about once an hour and manually cleaned with hypochlorite (15%) and hydrochloric acid (20%) as needed or about once every three months. Nanofilters are backwashed after every treatment cycle (around every 40 min) and chemically cleaned once a week with alternating acid (15% hypochlorite and 20% hydrochloric acid) and base (sodium hydroxide, 25%). Backwash water is then added back into the collection tank to be treated with the mainstream.

Sampling and analysis

Flow proportional 24-h samples were taken from the influent ($n = 82$) and nanofilter permeate ($n = 53$), and grab samples were taken from the sedimentation effluent ($n = 82$) every Wednesday morning. Samples were analyzed for COD, total and volatile suspended solids (TSS and VSS, respectively), total nitrogen (TN), ammonia (NH_4-N), nitrate (NO_3-N), total phosphorus (TP), and phosphate (PO_4-P). Samples were filtered through Munktell Filter Paper (Grade 1002, retention: 6–10 μm) before being analyzed for COD, TN, NH_4-N, TP, and PO_4-P using Hach Lange cuvettes on undiluted samples. TSS and VSS were determined via the method SS 02 81 12 for influent and sedimentation effluent only, and nitrate was analyzed using Hach method 10049. BOD_7 was measured externally for influent greywater only at an accredited laboratory according to the SS-EN ISO 5815-1:2019 method every 3 days. The same external lab was used to verify the concentrations of NH_4-N (ISO 15923-1:2013 B), TN (SS-EN ISO 20236:2021), TP (SS-EN ISO 15681-2:2018), and COD (ISO 15705:2002) once every 4 weeks. Uncertainties of methods can be seen in Table S1 in the Supplementary material. The average difference between internal laboratory values and external verification for NH_4-N was 7%, TN was 9%, TP was 1%, and COD was 8%. These differences were small enough that they did not affect the conclusions of this study.

RESULTS AND DISCUSSION

Because limited knowledge exists on operating greywater treatment and source-separated wastewater systems at such a large scale, like at RecoLab, much of the first two years have been learning through trial and error in conjunction with an increasing flow as more buildings were opened in the new city district Oceanhamnen. For example, the initial settings of the nanofilters caused greywater to build up in the inlet collection tank when the drum filtration was shut down. This would eventually trigger the high-water level emergency outflow, causing a high flow rate and washing sludge out of the biological treatment and into the sedimentation tank. This caused periods between 4 and 7 weeks where sedimentation effluent values were elevated. By adjusting the pump settings, this issue was resolved, and the treatment process ran smoother. In fact, the only operational issues were sludge washout due to high flow rates into the greywater biology. The downstream nanofilter did not have any operational issues during the 2-year initial period including start up (except for some minor adjustments of alarm levels to avoid triggering alarms during normal operation). As evidenced by this low breakdown rate, drum filters with a 10 μm screen seem to be an adequate pretreatment for nanofiltration.

Treatment efficiency

Over the course of the first two years, nitrogen, phosphorus, and organic matter were all removed enough to meet both the proposed changes to the UWWTD and the current environmental permit of Öresundsverket wastewater treatment plant in which RecoLab operates. The trends of COD, TN, and TP concentrations at different stages across the first two years of treatment are shown in Figure 3.

In the greywater influent to RecoLab, there was a COD:TN:TP ratio of 266:8:1 and BOD:NH_4:PO_4 ratio of 450:7:1. Using COD and BOD to total organic carbon (TOC) conversions established in mixed wastewater by Dubber & Gray (2010), this translates to a TOC:TN:TP ratio of 80:8:1 and a TOC:NH_4:PO_4 ratio of 264:7:1. A summary of C:N:P ratios in influent greywater at RecoLab and recommended nutrient ratios is presented in Table 2. For context, a nutrient ratio of 15–25:1 BOD:TP is recommended for EBPR processes (USEPA 1987; Feng *et al.* 2022). EBPR was the process opted for at RecoLab despite an influent BOD:TP ratio of 120:1. This means that influent greywater was deficient in phosphorus, specifically biologically available phosphorus. Biofilm processes perform slightly better in phosphorus-deficient environments, able to work at ratios as low as C:N:P ratio of 300:5:1 (Tay *et al.* 2003), but phosphorus limitation at RecoLab would still be present if EBPR was to be used. Theoretically, this means that carbon and nitrogen should have remained in high concentrations in the effluent from the sedimentation tank since excess phosphorus uptake by phosphorus-accumulating organisms reduces phosphorus available to be used in aerobic heterotrophic growth processes (that remove BOD). However, phosphorus is the only parameter that does not meet the suggested UWWTD limits (Table 1) after biological treatment, indicating that the COD:TN:TP ratio may be a more effective measure of biodegradability in this wastewater than BOD:NH_4:PO_4. It also shows that greywater can be treated effectively with biological processes. The next paragraphs take an in-depth look at the biodegradability and fractionation of nutrients in greywater.

When greywater entered RecoLab, about 45% of the COD was biochemical. While data did not exist to make conclusions about the removal of BOD, COD was reduced to 9 mg/L. In conventional treated wastewater, the COD:BOD ratio can be higher than 4 (Shestakova *et al.* 2020), meaning that BOD could have been as low as 2 mg/L in effluent greywater from RecoLab based on the effluent COD concentration. The UWWTD proposal (Table 1) has a limit of 25 mg/L BOD_5, and the current environmental permit has a limit of 10 mg/L BOD_7. Since effluent COD concentrations were below both of these limits, it can be concluded that BOD was removed sufficiently at RecoLab.

Looking at nitrogen, influent wastewater contained 15.4 mg/L TN with about 24% or 3.65 mg/L as NH_4-N and 5% or 0.70 mg/L as NO_3-N. After sedimentation, TN was reduced to 4.9 mg/L and NH_4-N accounted for only 5% or 0.25 mg/L NH_4-N of TN, while nitrate accounted for 8% or 0.40 mg/L NO_3-N. A summary of these values is presented in Table 1. Although nitrate concentrations during the first two years made up about 5% of incoming nitrogen, more recent data have shown that nitrate has not been detectable in influent greywater since August 2023, indicating that high nitrate concentrations could be related to the construction and new habitation of buildings rather than what is being put into the sewer network.

Most of the ammonia in influent greywater would have gone through nitrification to become nitrate before being denitrified, leading to a reduction in both forms of nitrogen overall. However, it appears that from the sedimentation tank through the nanofilters nitrate concentrations increased and accounted for 30% or 0.77 mg/L

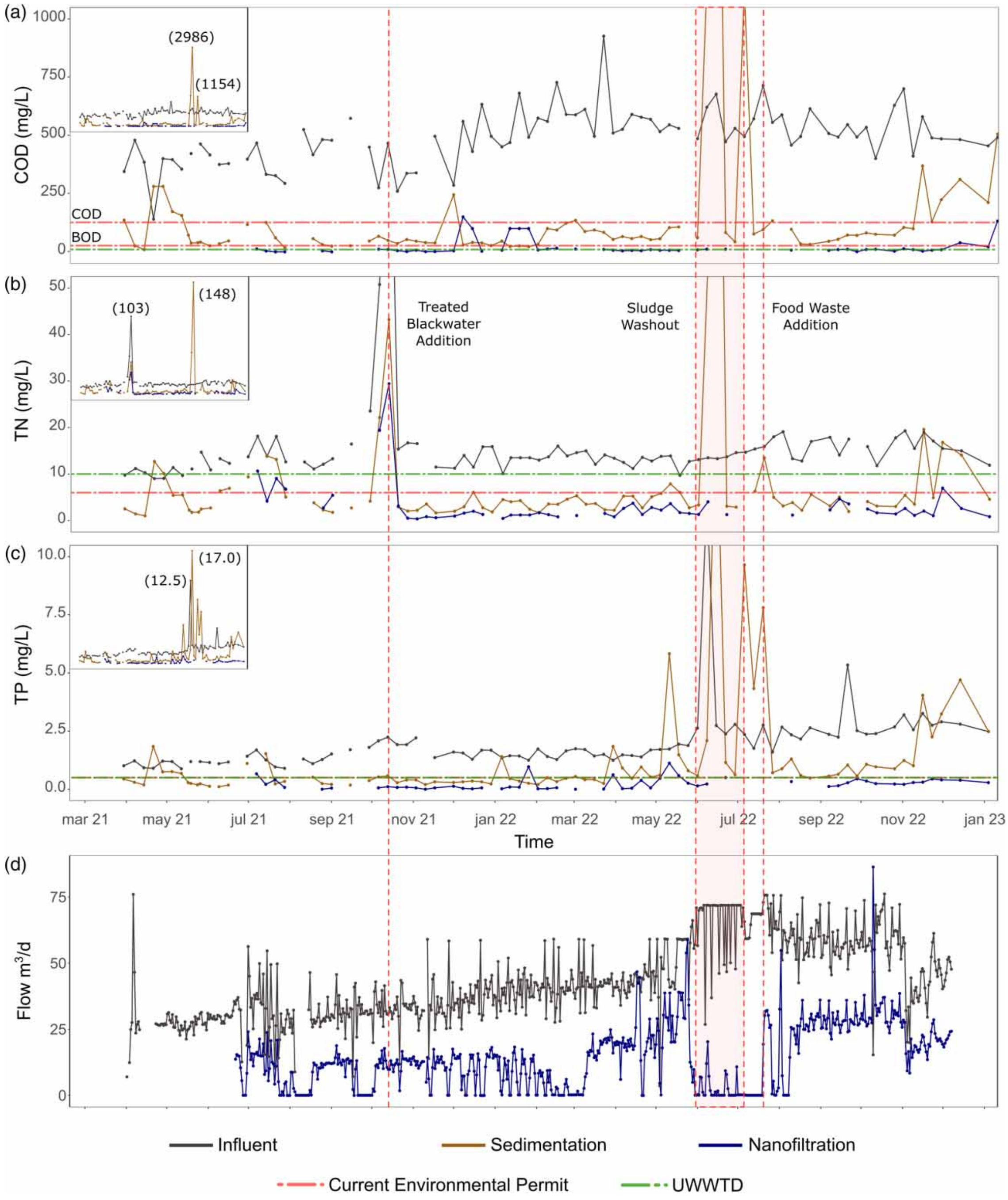


Figure 3 | Concentration of COD (a), total nitrogen (b), and total phosphorus (c) in influent (grey), after sedimentation (brown), and after nanofiltration (blue) greywater as well as the influent and nanofilter permeate flows (d) at RecoLab. Shaded areas and vertical dashed lines mark anomalies in the operation in chronological order; addition of blackwater, sludge washout, and addition of food waste. Sampling occasions are denoted with a point and discharge limits are denoted with horizontal dash-dotted lines.

NO_3-N of the 2.6 mg/L TN present in nanofilter permeate, while ammonia accounted for only 4% or 0.11 mg/L NH_4-N. This could indicate poor denitrification in biological treatment. It is important to note that higher levels of uncertainty in analyses of low concentrations, specifically in the instance of nitrate here (±0.1 mg/L), could account for the apparent increase in nitrate concentration across the membranes. Regardless, there was still 70% of the TN present in other forms in incoming greywater and 76% in nanofilter permeate. This is compared to ammonia making up 64% of incoming nitrogen and 20% of outgoing nitrogen in mixed wastewater produced in the same city (NSVA 2022). Preliminary results indicate a significant portion of nitrogen in greywater is

Table 2 | Nutrient ratios

	C:N:P
Influent greywater	
COD:TN:TP	266:8:1
BOD_7:NH_4:PO_4	450:7:1
TOC^a:TN:TP	80:8:1
TOC^a:NH_4:PO_4	264:7:1
Recommendations	
Aerobic activated sludge	100:5:1
Anaerobic activated sludge	250:5:1
Enhanced biological phosphorus removal (BOD:TP) (Feng *et al.* 2022)	15–20:1
Biofilm processes (Tay *et al.* 2003)	300:5:1

[a] TOC estimated based on COD and BOD concentrations and conversions established by Dubber & Gray (2010).

potentially organically bound due to its apparent reduction through coagulation in jar tests (data not published). The relative removals of nitrogen species support the hypothesis that a large portion of nitrogen in greywater is organically bound, even in the permeate after nanofiltration. If true, this high portion of organically bound nitrogen could be a result of low residence time in the sewer network, reducing the amount of hydrolysis that occurs on the way to the treatment plant. Another possibility is that the main contributor of nitrogen to the greywater stream is food waste, compared to urine in mixed wastewater or fertilizers in surface runoff.

Regarding phosphorus, influent greywater contained 1.99 mg/L TP with only 27% or 0.53 mg/L entering RecoLab as PO_4-P. While orthophosphate (PO_4) is the form that is biologically available, the relative proportion of PO_4 to TP present increased to 37% after sedimentation and 81% after nanofiltration. This corresponds to concentrations of 0.65 mg/L TP and 0.24 mg/L PO_4-P after sedimentation and 0.21 mg/L TP and 0.17 mg/L PO_4-P after nanofiltration. A summary of these values is presented in Table 1. For comparison, a report on the speciation of phosphorus in municipal wastewater from another large wastewater plant in Sweden found that 79% of incoming phosphorus and 70% of outgoing phosphorus was orthophosphate (Rehnberg 2021). The low percentage of biologically available phosphorus in greywater influent could potentially limit the biological stage of treatment if there is not sufficient hydrolysis. However, it does not seem to have diminished the efficacy thus far. The increase in relative concentration of orthophosphate could be due to the hydrolysis of polyphosphates into orthophosphate and/or the settling of particulate phosphorus. Effluent phosphate concentrations could potentially be reduced further with the addition of coagulants since most coagulants react primarily with orthophosphate (Shestakova *et al.* 2020).

From Table 1, it can be seen that both TSS and VSS were reduced to below 35 mg/L, the limit of effluent TSS in the UWWTD proposal, after sedimentation. Influent TSS and VSS concentrations were around 140 ± 50 mg/L, but their variation did not seem to correlate with a change in the efficacy of treatment. Variations in TSS and VSS concentrations of the sedimentation effluent (18 ± 16 mg/L) were not the cause but instead a result of poor biological treatment operational settings. TSS and VSS concentrations were not measured after nanofiltration. The pH of influent and sedimentation effluent greywater was stable around 7.2 ± 0.3 and increased to 7.8 ± 0.3 after nanofiltration. The changes in pH did not appear to correlate to any of the breakdowns in treatment or changes in treatment efficacy.

Considering long periods of stable operational data (October 2021–June 2022 and September 2022–January 2023), the nanofilter permeate was consistently around 10 mg/L COD, 2 mg/L TN, and 0.2 mg/L TP. These concentrations are under the current environmental permit limits for the main wastewater treatment plant (Öresundsverket) that houses RecoLab: yearly averages of 10 mg/L TN, 0.5 mg/L TP, and 10 mg/L BOD_7. The environmental permit also recommends a yearly effluent average of 0.3 mg/L TP. This was fulfilled by RecoLab.

Operational anomalies

During the first two years of operation, there were a few operational anomalies that occurred. A timeline of operational events is shown in Figure 2. Three of those anomalies are discussed here: the addition of treated blackwater to the greywater line, a sludge washout event, and the addition of food waste to the greywater line.

These three major events are also denoted in Figure 3. The addition of food waste to the greywater line occurred when food waste pipes in the collection system were blocked. This occurred three times with the largest addition lasting 3 days. Blackwater addition occurred due to the accidental addition of effluent from the treated blackwater stream, which was supposed to be sent to the sewer but instead was directed to the greywater collection tank, totaling about 4 m^3 of treated blackwater being added to the greywater tank over the course of 1 day.

Looking at the addition of treated blackwater that occurred in October 2021, both sedimentation effluent and nanofilter permeate were affected. It was also clear that the addition of blackwater did not equally affect COD, TN, and TP. Since the blackwater had already undergone digestion, much of the COD was removed prior to its addition. In addition, phosphorus precipitation in the form of struvite from the digested blackwater removed a large portion of phosphates, while nitrogen stripping in the blackwater was not fully functional. Therefore, nitrogen had the largest peak at all sampling points in the greywater treatment train, while COD only had a clear peak in the influent and phosphorus had almost no difference at all, even in influent greywater.

Comparing the addition of treated blackwater to the addition of untreated food waste that occurred in July 2022, there was a very clear spike in carbon and phosphorus concentrations in the influent greywater. Nitrogen concentrations in the influent did increase but seemed in line with the local trend. However, both nitrogen and phosphorus concentrations spiked in the sedimentation effluent. COD increased as well but data do not exist to determine whether it was within the local trend or a spike. Nanofilter data around the same time do not exist since nanofilters were bypassed due to a sludge washout event that occurred before the addition of food waste.

The other major event that occurred during operation was a large sludge washout event in June 2022. This was shortly after the expansion of the biological treatment step into the larger section of the treatment basins to accommodate an increase in flow as residents moved into newly completed buildings in the service area and flow stabilized. COD, TN, and TP all showed large spikes in sedimentation effluent concentrations. Nanofiltration data through the entire event do not exist since nanofiltration was bypassed to protect the membrane during the operation malfunction. However, permeate data from the very beginning of the washout showed slight increases in concentrations for all three parameters that are less pronounced than sedimentation effluent. In addition, similar spikes in the sedimentation effluent at other times did not show a corresponding increase in nanofilter permeate concentrations as for sedimentation effluent concentrations. However, it appears that nitrogen was the most effected by sludge washout in the nanofilter permeate, likely due to a reduced efficacy of the biological treatment and poor removal of nitrogen by the nanofilters. This phenomenon aligns with the existing literature that shows that membranes can struggle to remove nitrogen in comparison to organic matter and phosphorus (Santasmasas *et al.* 2013; Jabornig & Podmirseg 2015; Fountoulakis *et al.* 2016). The continued low nanofilter permeate concentrations even when sedimentation tank effluent concentrations were high indicated that nanofiltration is acting as a redundancy to biological treatment and could be somewhat effective at removing nutrients. However, nanofiltration is not as good at removing nitrogen compared to carbon and phosphorus. In the seven months after the sludge washout event between June 2022 and January 2023, it was challenging to re-establish stable biology and nanofilters have helped to ensure a high-quality effluent. Less-intense sludge washout events have occurred more often, and the biological treatment stage has needed to be reinoculated multiple times during the second year of operation as opposed to only once during the first year. Ongoing investigations are being completed to re-establish stable operation.

Micropollutants

Studies on micropollutants in greywater show that a majority of micropollutants in greywater originate from detergents, soaps, bleach, and perfumes (Hernández Leal *et al.* 2010). A literature review of articles from Sweden, Denmark, and the Netherlands in 2015 found that eight phthalates were present in similar or lower concentrations than seen in traditional influent wastewater, and five of the eight were present in higher concentrations than traditional effluent wastewater. However, the concentration of four micropollutants commonly used in personal care products was substantially higher than in traditional mixed wastewater (Etchepare & van der Hoek 2015). Early studies on micropollutants in greywater (Eriksson *et al.* 2002, 2003; Palmquist & Hanaeus 2005; Almqvist & Hanæus 2006) focused on the presence of micropollutants and lack of quantitative information and therefore general health risks.

More recent greywater micropollutant studies have shifted focus toward pharmaceuticals (Butkovskyi *et al.* 2015; Tombola *et al.* 2019; Zraunig *et al.* 2019; Glover *et al.* 2021) and have started to quantify their presence and potential risks. Most pharmaceuticals are diverted to the blackwater stream but are potentially still present in greywater, especially if they are available as topical creams (Etchepare & van der Hoek 2015; Butkovskyi *et al.* 2017). The presence of Per- and polyfluoroalkyl substances (PFAS) and at what concentrations they exist in greywater have not been reported yet (Shaikh & Ahammed 2020). Glover *et al.* (2021) noted that abnormally high concentrations of PFAS were found in aquatic environments near where greywater was used for irrigation. With improved detection limits, the understanding of what micropollutants exist in greywater and their apparent risks are in the process of being fully understood, but there are still large knowledge gaps.

Micropollutant removal during nanofiltration in the same type of nanofilters as in RecoLab has been further studied by Rutten *et al.* (2023). They found that the nanofilters used in RecoLab retain more than 85% of eight pharmaceutical micropollutants and two personal care product micropollutants.

CONCLUSION

After two years, RecoLab's activated sludge-drum filter-nanofiltration greywater treatment line has been able to achieve stable effluent concentrations below 10 mg/L COD, 2 mg/L TN, and 0.2 mg/L TP as yearly averages. These effluent concentrations meet both the proposed changes to the UWWTD and the current environmental permit of the wastewater treatment plant where RecoLab is housed. Despite apparent phosphorus limitations, activated sludge treatment alone was effective at removing nitrogen (down to 4.9 mg TN/L) but failed to remove phosphorus (0.65 mg/L TP) to below the 0.5 mg TP/L requirement. Nanofiltration removed enough remaining phosphorus to meet effluent demands for both the UWWTD and the current environmental permit and further reduced residual nitrogen concentrations while reducing the residual COD concentration below the requirements for BOD. The relative removal of different species of nitrogen indicated that a large portion of nitrogen in the effluent could be organically bound. Finally, as indicated by the lack of breakdowns in the nanofiltration stage, drum filters seem to be an adequate pretreatment for nanofiltration.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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