Special Series

Membrane Bioreactor–Treated Domestic Wastewater for Sustainable Reuse in the Lake Victoria Region

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EDITOR'S NOTE:

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ABSTRACT

Lake Victoria is a shared water resource between Kenya, Uganda, and Tanzania, which is the second largest freshwater lake in the world. It has long since suffered from the consequences of overexploitation of its resources, mainly fish stocks, and increasingly high pollution. The closure of 58% of the fish processing plants (FPPs) is attributed to the declining fish stocks due to overfishing and pollution in particular. The installation and operation of a pilot membrane bioreactor (MBR) in Kisumu, Kenya, adopts an integrated approach by providing an integral, sustainable, cost-effective, and robust solution for water sanitation, which also meets the demand for clean water in the fish processing industry, aquaculture, and irrigation. The innovative system comprises a pilot MBR coupled with a recirculation aquaculture system (RAS). The RAS is able to re-circulate 90% to 95% of its water volume; only the water loss through evaporation and drum filter back flushing has to be replaced. To compensate for this water deficit, the MBR treats domestic wastewater for further reuse. Additionally, excess purified water is used for irrigating a variety of local vegetables and could also be used in FPPs. The pilot-scale MBR plant with around 6 m² submerged commercial polyethersulfone (PES) membranes provides treated water in basic agreement with Food and Agriculture Organization (FAO) standards for irrigation and aquaculture, showing no adverse effects on tilapia fingerlings production. A novel membrane module with a low-fouling coating is operating stably but has not yet shown improved performance compared to the commercial one. *Integr Environ Assess Manag* 2020;16:942–954. © 2020 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC)

Keywords: Membrane bioreactor   Low-fouling membrane coating   Recirculating aquaculture system   Domestic wastewater   Water reuse

INTRODUCTION

Lake Victoria is a shared water resource between Kenya, Uganda, and Tanzania. It is the second largest freshwater lake in the world and originally contained a diverse array of some 400 species (Reinertsen and Halland 1995). It is of key socioeconomic relevance for the region because it supports a population of about 30 million people through large-scale fishing, agriculture, local industries, tourism, and related activities. Despite its crucial importance, Lake Victoria has

long suffered from the consequences of decades of exploitation of its resources—mainly of its fish stocks—and alarming pollution rates. Many efforts have been put in place in recent years to ameliorate the current situation. However, there are still societal and technical challenges that require prompt responses.

The main challenges around the lake include (Weitz 2019) 1) rapid urbanization, 2) very high population density (the region surrounding the lake is the most densely populated rural area in Africa), 3) high rate of poverty (the percentage of people living below the poverty line [<\$1] is as high as 50%), 4) poor sanitation and water provision infrastructure, 5) weak law enforcement, and 6) lack of awareness of the environmental impact of fisheries and wastewater disposal. In 2003 the total biochemical oxygen demand (BOD), N, and P load to Lake Victoria from domestic wastewater totaled 17 938, 3505, and $1624 \, t \cdot y^{-1}$, respectively (LVEMP 2003). The respective industrial load summed up to 5606, 414, and $342 \, t \cdot y^{-1}$. At around 75%, wastewater from agriculture is the main source of the lake's increasing nutrient pollution load (El-Noshokaty 2017). Wastewater from the region's agriculture undergoes virtually no treatment.

In the Lake Victoria area, as in many other regions in Sub-Saharan Africa, treatment of domestic wastewater by waste stabilization ponds (WSPs) is very popular because they are easy and inexpensive to operate and maintain. The main processes include anaerobic ponds, facultative ponds, and maturation ponds. Conventional treatment processes such as activated sludge and biofilms are seldom used in Africa due to lack of energy and financial resources (Wang et al. 2014). However, WSPs have the disadvantage of large land requirements and low biodegradation rates, particularly for N and P removal. In urban areas, off-site treatment is also a common practice, involving the collection and transportation of wastewater to wastewater treatment plants. In Kenya, out of the 39 publicly operated wastewater treatment systems, there are 27 waste stabilization ponds, 6 conventional processes such as trickling filters, 3 oxidation ditches, and 3 aerated lagoons (Wang et al. 2014).

Membrane bioreactor (MBR) technology, which is the combination of the common activated sludge process and microfiltration and/or ultrafiltration (MF/UF), has attracted great academic attention over the last 3 decades and achieved rapid growth in an increasing number of practical small- and large-scale applications worldwide (Xiao et al. 2019). The main benefits of MBR application include high effluent quality (for water reuse), small footprint, and complete separation of hydraulic retention time (HRT) and solids retention time (SRT). Membrane bioreactors also show better removal for a variety of micropollutants and microplastics compared to that of conventional wastewater treatment plants due to the complete retention of suspended solids and higher sludge concentration at higher SRT (Lares et al. 2018; Xiao et al. 2019). Up to now, larger scale application of MBR technology in Africa was limited mainly to the Northern Africa region and to South Africa (Skouteris et al. 2014; MBR site 2019). The largest MBR unit

was commissioned in 2018 in Stellenbosch, South Africa, with a daily peak flow of 67.5 minimal liquid discharge (MBR site 2019). Likewise, MBR technology offers water treatment and reuse options in other African regions due to its modularity and simple scalability, in particular for decentralized applications in agriculture and aquaculture. Therefore, the main objective of the present study is to demonstrate the viability of a pilot MBR with a $6.25 \, m^2$ membrane area, treating domestic wastewater to compensate the water loss in recirculating aquaculture systems (RAS) as part of the European Union (EU)–funded VicInAqua project (2019) in Kisumu, Kenya (Supplemental Data Figure S-1).

One of the main drawbacks of MBR is its membrane-fouling propensity and the resulting high energy consumption, contributing to higher operational expenditures (Drews 2010; Deowan et al. 2016; Meng et al. 2017). To overcome the membrane-fouling problems, many researchers have modified and tested membranes, applying different techniques (Deowan et al. 2016). Particularly in the African environment, low-fouling membranes will be very beneficial because they require fewer chemicals for cleaning and are low maintenance, which greatly simplifies the operation of MBRs. Membranes for wastewater reuse are exposed to fouling phenomena such as inorganic and organic fouling as well as biofouling. This major drawback increases the specific energy consumption of MBR systems in the long run. Researchers have therefore focused on membrane modification strategies to mitigate fouling, which is generally affected by properties such as hydrophilicity, surface charge, and roughness. In general, the surface of membranes can be modified chemically by adsorbing components to or attaching macromolecules to a membrane surface (grafting) by different treatment units using chemicals, UV irradiation, and plasma (Saqib and Aljundi 2016; Chang et al. 2019). For instance, Bae and Tak (2005) entrapped titanium dioxide particles in an additional membrane coating layer and reduced the flux decline over time. Kim et al. (2014) incorporated quorum-quenching bacteria into polymeric membranes and minimized the specific transmembrane pressure (TMP) increase during lab-scale tests.

A promising approach to mitigate the fouling was further developed by membrane surface modification based on polymerizable bicontinuous microemulsion (PBM) technology (Galiano et al. 2015, 2018; Deowan et al. 2016). They used a PBM as a low-fouling layer polymerized on ultrafiltration (UF) polyethersulfone (PES) membranes. A microemulsion is a thermodynamically stable dispersion consisting of 2 immiscible liquids (generally oil and water) stabilized by a surfactant. For the formation of a microemulsion, suitable monomers, usually dispersed in the oil channels, can be used as components. They are optically transparent with a small droplet size (10–200 nm) and low interfacial energy and they can be easily casted on top of commercial membranes and polymerized by UV light-emitting diode (UV-LED) light. The PBMs exhibit antimicrobial properties (low biofouling) and produce polymeric

micro- and nanostructured solid materials, which can be tuned in terms of their rejection characteristics (e.g., molecular weight cut-off [MWCO]) depending on polymerization conditions (Temperature, PBM composition). Hence, this is an ideal technique for membrane functionalization, resulting in an innovative hydrophilic and low-fouling coating material particularly for application in MBRs. The PBM used in the present deployment contained a home-made surfactant with an antimicrobial quaternary ammonium group and a cosurfactant with a hydrophilic head. The lower-fouling propensity was also achieved by a reduction in surface roughness. So far PBM induced with UV-LED light has not been applied for pilot-scale treatment of real wastewater and was used for the first time for pilot experiments within the present study.

A further objective, therefore, was on-site testing of the novel PBM-based membranes for fouling propensity and long-term stability in direct comparison with a commercial one. Based on the pilot findings, finally a simple low-cost, small-scale MBR with $10\,m^2$ membrane area for decentralized wastewater treatment in the Lake Victoria region is presented, together with potential application sectors.

MATERIALS AND METHODS

Membrane bioreactor pilot

The VicInAqua pilot plant was set up next to Nyalenda waste stabilization ponds in Kisumu, Kenya, which treat an average of $29\,000\,m^3$ of domestic wastewater per day. The raw sewage inlet was tapped to feed the pilot MBR with a submersible pump Pedrollo VXCm 15/45 (Figure 1, part 1.1) over a distance of approximately 200 m (Figure 1, top, far left image). Thereby, wastewater first passes through a 2.5 mm strainer and a second plastic screen with a 1 to 2 mm mesh size, respectively, before it is collected in a 3-m^3 buffer tank. A cartridge filter with a 0.8 mm mesh size was installed in front of the MBR to further minimize the entry of solid particles. The illustrated process in Figure 1 gives a more detailed system overview. Depending on the water level inside the MBR, the submersible feed pump (Jung U3KS) (Figure 1, part 2.1) inside the buffer tank fills the water level to a preset value by simple on/off control. Basically, the MBR tank is divided into 3 compartments for denitrification (Figure 1, part 3), biological degradation and nitrification (Figure 1, part 4), and filtration (Figure 1, part 5) with volumes of 0.7, 0.44, and 0.56 m^3, respectively.
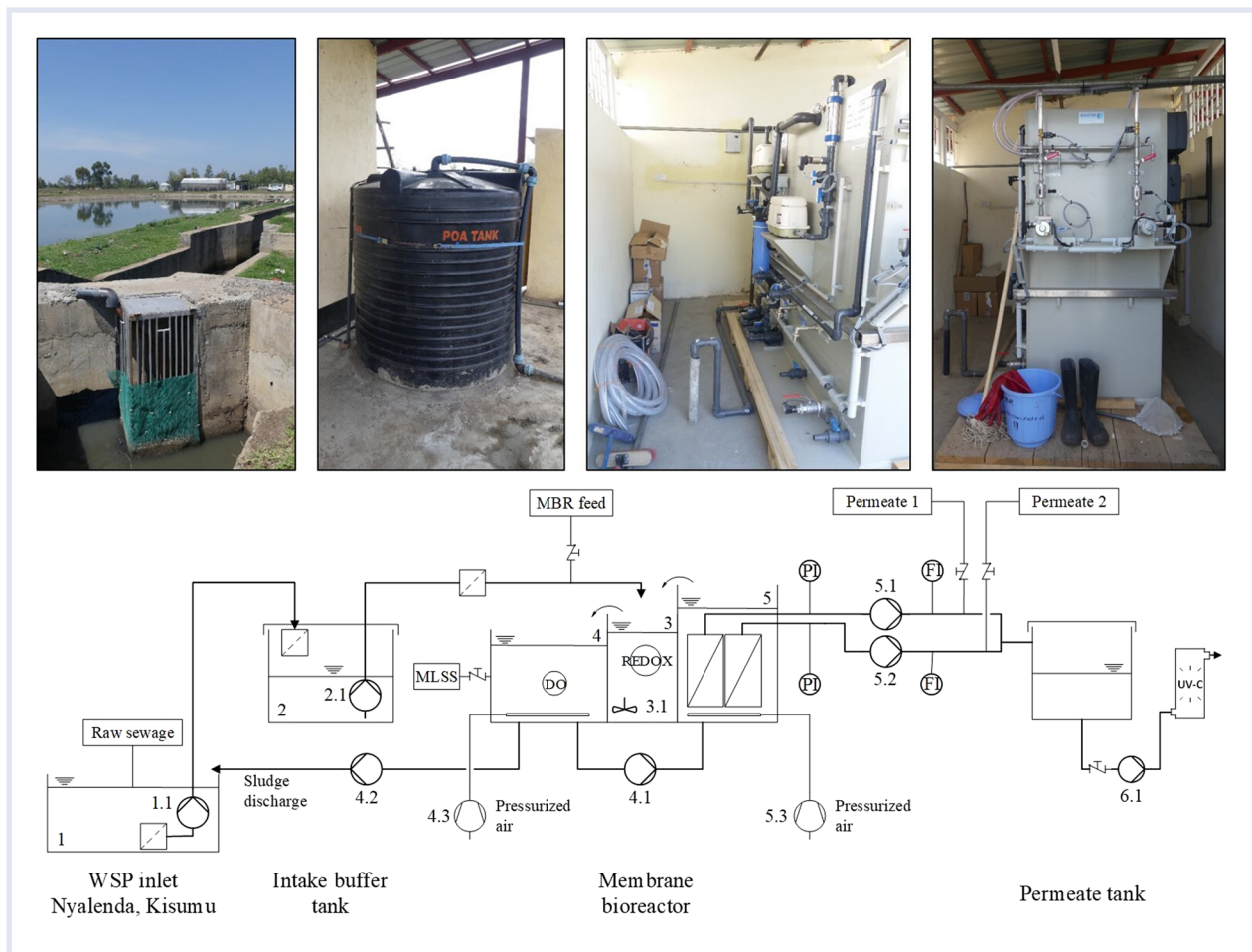

Figure 1. Visual impression of the pilot MBR implementation within VicInAqua in Kisumu (top) and schematic diagram (bottom). MBR = membrane bioreactor; MLSS = mixed liquor suspended solid; WSP = waste stabilization pond.

Wastewater treatment inside the MBR is as follows (Figure 1): Prefiltered wastewater enters the anoxic denitrification compartment where nitrate (NO_3^-) is reduced to gaseous N_2. A Jebao Jecod SW15 mixer (Figure 1, part 3.1) prevents activated sludge from settling, which would hamper water treatment. Through the overflow, wastewater subsequently flows into the aerobic degradation–nitrification compartment where C components are degraded and ammonium (NH_4^+) is oxidized into nitrate. On/off control of the blowers (Figure 1, parts 4.3 and 5.3), providing O to the bacteria, is realized by an integrated dissolved oxygen (DO) sensor (OxyGuard D0243C) to keep the DO level in the range of 2 to 3 $mg \cdot L^{-1}$. From the degradation–nitrification compartment, the recirculation pump (Figure 1, part 4.1) pumps the water into the aerobic filtration chamber where permeate is drained through 2 UF membrane modules in parallel, each with an area of 3.125 m^2 (Polymer: PES; MWCO: 150 kDalton; pore size: nominal 35 nm) (MARTIN Systems 2019). The 2 permeate pumps (Figure 1, parts 5.1 and 5.2) of the UF modules were both operated alternately, 12 min in suction and 3 min in relaxation mode. Installed diffusers below the membrane modules, connected to an intermittent blower, enable sufficient cross-flow rates resulting in fouling mitigation. Part of the wastewater flows back from the filtration chamber into the denitrification compartment by overflow. Despite the fact that UF membranes are able to ensure almost complete germ removal for safety purposes, a UV-C lamp (AQUASTERA, type ASUV27) was installed downstream from the 2 m^3 permeate collection tank. Finally, a circulation pump (Figure 1, part 6.1) distributes the purified water from the permeate tank into the RAS and agriculture for further reuse.

Polymerizable bicontinuous microemulsion–based membrane coating

Deploying the PBM coating aims to improve the filtration process in terms of lower membrane-fouling propensity. This low-fouling technology was applied for the first time at the size of a 3.125 m^2 membrane area to examine the benefits compared to commercial PES membranes. A microemulsion is a heterogeneous mixture usually comprising an oil and water phase. Amphiphilic surfactants provoke a sharp reduction in surface tension, enabling a fine dispersion between both phases. Depending on the type and quantity used, the PBM composition chosen can affect the droplet size and geometry in a different manner and create a globular, lamellar, or in this case a bicontinuous structure. Within the present work, the self-developed and synthesized antimicrobial surfactant acryloyloxyundecyltriethylammonium bromide (AUTEAB) (Figoli 2014) is incorporated into the microemulsion with the methylmethacrylate (MMA) as the oil phase. The supportive acting cosurfactant 2-hydroxyethyl methacrylate (HEMA) also improves the hydrophilic behavior by its hydroxyl group (–OH). Finally, the thermodynamically stable PBM is formed and stabilized by the cross-linker 1,2-Ethanediol dimethacrylate (EGDMA). After mixing the components,

the microemulsion forms spontaneously. Galiano et al. (2015, 2018) and Deowan et al. (2016) have successfully tested the feasibility of coating polymer (PES) membranes in various laboratory studies. Originally, considerations about forming a PBM for membrane application were made by Gan and Chew (1997). The next logical consequence was the extensive testing of PBM-coated membranes on a larger scale, treating real wastewater.

Initial coatings using casting knifes of different thickness (4–450 µm) were done on small membrane areas of 0.0084 m^2 for lab-scaled application and 0.06 m^2, subsequently laminated to a 0.33 m^2 membrane module. For further upscaling to a 3.125 m^2 membrane module, an automated coating device was developed capable of coating commercially available big flat sheet membranes around 0.1 m^2.

Process monitoring using temperature, DO, and humidity sensors increased the reproducibility and thus the production quality. For the final curing on the commercial PES flat sheet membrane, the photoinitiator Irgacure 184 was activated by UV-LED light at a wavelength of 365 to 410 nm to start the polymerization reaction. Irradiation intensity has a high impact on the polymerization degree, which is also dependent upon curing time. For the membrane production, the irradiation intensity and time were set to 300 $mW \cdot cm^{-2}$ and 60 s, respectively (Galiano 2018).

Subsequently, MARTIN Systems laminated the coated PBM flat membrane sheets, resulting in the final 3.125 m^2 module. For performance tests in the pilot MBR, 1 pristine PES membrane module was run in parallel with the PBM module, installed in permeate line 1 (see also Figure 2, bottom).

Wastewater quality

A full analysis of wastewater quality was carried out twice at the analytical laboratory of Karlsruhe University of Applied Sciences, Germany, during operation periods 1 and 2 (see Figure 3), whereas raw sewage is taken from pond inlet and MBR feed after having passed all upfront strainers (Figure 1, bottom; Table 1). It should be noted that the wastewater quality of raw sewage at the Nyalenda waste pond could vary greatly because, in addition to continuous inflow, wastewater from lorries, also collected in the nearby quarter, was frequently discharged into the feed channel.

The electrical conductivity and pH were measured with handheld units: WTW Cond 315i and WTW pH 325, respectively. The ion chromatograph Metrohm 883 Basic IC plus (column: Metrosep A Supp 4) was used for ion measurement. The total organic carbon (TOC), total inorganic carbon (TIC), and total nitrogen (TN) were determined using the TOC analyzer (Model: TOC-L CPH/CPN, Shimadzu). The chemical oxygen demand (COD) was analyzed with COD cell tests (1.14541) and spectrophotometer Spectroquant NOVA 60 from Merck KGaA (Germany).

During the trials, a spectrophotometer Spectroquant NOVA 60 and the following cell tests were used at the pilot site in Kisumu: 1) COD cell tests (1.14541), 2) ammonium cell test (1.14752.0001), 3) nitrate cell test (1.14542.0001), and 4) phosphate cell test (1.14729.0001), all from Merck
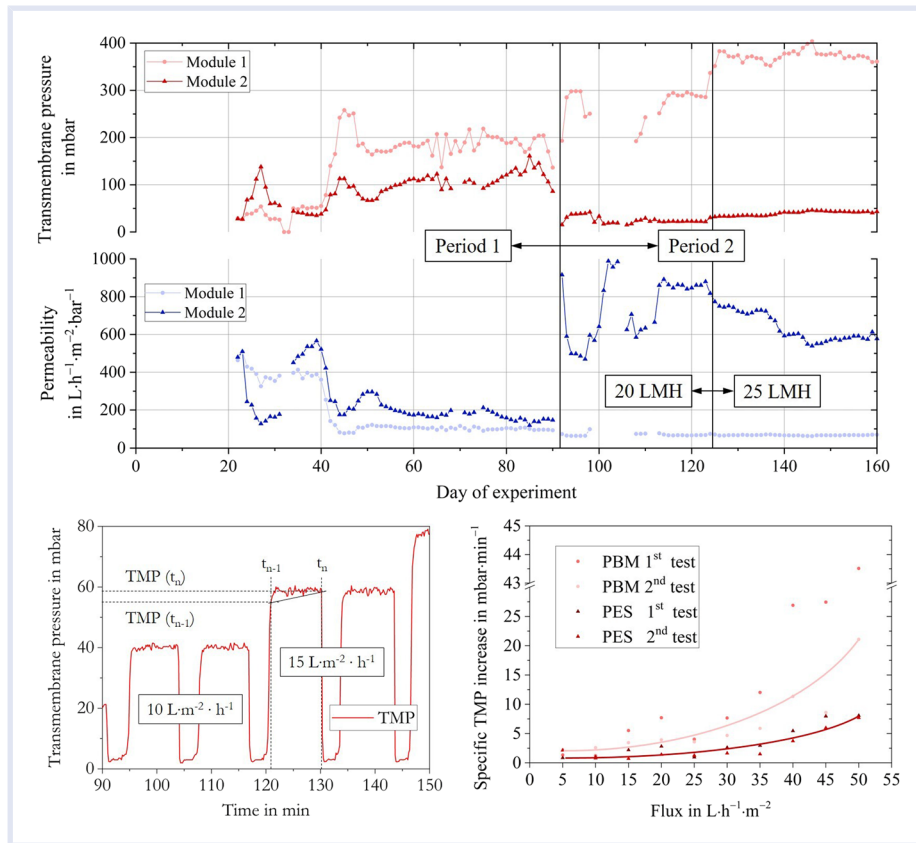
Figure 2. Membrane performance comparing both modules (top) and flux step tests showing the flux dependent on the specific pressure increase (bottom). LMH = L m^{-2} h^{-1}; PBM = polymerizable bicontinuous microemulsion; PES = polyethersulfone; TMP = transmembrane pressure.

KGaA (Germany). The mixed liquor suspended solids (MLSS) were analyzed by drying residue of sludge samples from the nitrification tank minus the drying residue from the permeate (25 ml each) using the balance DELTA-500 (max. 500 ± 0.1 g).

RESULTS OF PILOT TRIALS

The pilot trials were essentially divided into 2 phases:

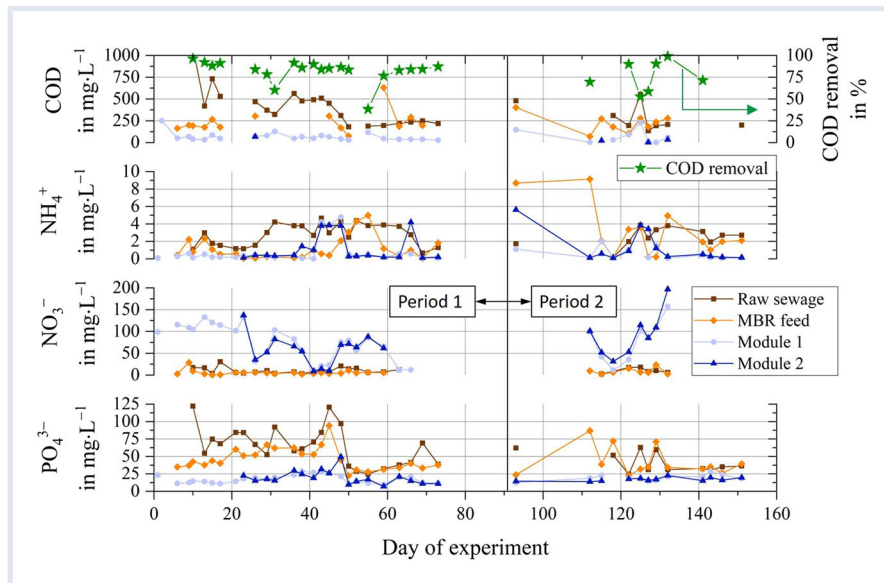1) Operation period 1 with 2 commercial PES modules (MARTIN Systems FM 621) in parallel.

Figure 3. Essential water parameters of the pilot MBR providing treated domestic wastewater for aquaculture and irrigation. MBR = membrane bioreactor.

Table 1. Wastewater quality at VicInAqua pilot site

Parameter	Unit	SD of method	Raw sewage		MBR feed		FAO standards	
			Sample 8 Feb 2019	Sample 22 May 2019	Sample 8 Feb 2019	Sample 22 May 2019	Aquaculture	Irrigation
pH	pH scale	±0.1	7.6[a]	7.1[a]	7.4[a]	7.5[a]	6.0–8.5	6.5–8.5
Conductivity	$\mu S \cdot cm^{-1}$	±10	1133[a]	837[a]	1034[a]	856[a]	Max. 3000	2500
COD	$mg \cdot L^{-1}$	±4.9	683[a]	580[a]	239[a]	438[a]	Max. 50	30
TOC	$mg \cdot L^{-1}$	±0.5	82.8	82.1	99	70.8	—	—
TIC	$mg \cdot L^{-1}$	±0.5	177.5	67.4	146	74.9	—	—
NH_4^+	$mg \cdot L^{-1}$	±0.1	53.9	42.8	36	46.5	Max. 5	1.5
NO_3^-	$mg \cdot L^{-1}$	±0.8	6.5	BDL	4.7	BDL	Max. 44	44
TN	$mg \cdot L^{-1}$	±1.0	107.4	60.0	75.5	65.1	—	—
PO_4^{3-}	$mg \cdot L^{-1}$	±0.1	39.2	10.2	32.2	14.3	Max. 2	0.1
SO_4^{2-}	$mg \cdot L^{-1}$	±0.8	33.9	42.8	28.0	43.0	—	—
Cl^-	$mg \cdot L^{-1}$	±0.5	86.5	72.3	71.8	75.0	—	—
Na^+	$mg \cdot L^{-1}$	±0.1	110.8	86.4	109.3	88.3	—	—
K^+	$mg \cdot L^{-1}$	±0.1	68.4	32.8	76.9	33.9	—	—
Mg^{2+}	$mg \cdot L^{-1}$	±0.5	25.0	15.0	232	16.0	—	—
Ca^{2+}	$mg \cdot L^{-1}$	±0.5	67.4	68.9	54.9	74.1	—	—

BDL = below detection limit; FAO = Food and Agriculture Organization of the United Nations; COD = chemical oxygen demand; TIC = total inorganic carbon; TOC = total organic carbon; TN = total N.
[a]Sample not filtered; all other samples were passed through paper filter (Schleicher & Schuell 589) prior to measurement.

2) Operation period 2 with 1 commercial and 1 novel module accommodation of 34 PBM-coated membranes (each module with a 3.125-m^2 membrane area).

Start-up

Prior to the trials using real wastewater, tap water tests were conducted in order to verify the functionality of the pilot unit and particularly to ensure proper performance of the 2 commercial membrane modules in operation period 1. The start-up phase also helped acclimation of the membrane pores (pore swelling), which was facilitated by lower water flux up to 20 $L \cdot m^{-2} \cdot h^{-1}$ (LMH). After acclimation, roughly constant water permeability of $620 \pm 20 \, L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$ was obtained, which is far above the manufacturer recommendation of $>250 \, L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$. Compressed air volume flow for both blowers, aeration and filtration chamber, were within the required range of 12 $m^3 \cdot h^{-1}$. Subsequently, clean water from the denitrification and nitrification compartment was discharged and refilled with around 500 L activated sludge from the Kisat municipal treatment plant in Kisumu. Specifically, activated sludge must be rich in aerobic bacteria, free of feces, oil, and solid and abrasive particles that may damage or clog the membranes.

The compartment volume was topped off with wastewater and the automated pilot MBR was started. The recirculation pump fed the activated sludge–wastewater mixture into the filtration chamber to be diluted by the clean water, enabling a slow adaption of the activated sludge. After homogenizing the volume in each compartment, the nitrification tank contained activated sludge of approximately 6 $g \cdot L^{-1}$ MLSS.

Water flux, transmembrane pressure, and permeability

The pilot trials were started with 2 commercial membrane modules submerged in activated sludge operated at a normalized water flow (water flux) of 13 LMH in order to acclimate the biocenosis. On day 33, water flux was increased to 20 LMH and maintained until replacement with 1 PBM and 1 virgin PES module at day 91. The total HRT for aerobic treatment in the nitrification compartment was 1.3 h and around 0.7 h for 1 circulation cycle (25 LMH) for the anoxic treatment. Calculations were based on the compartment volume and the recirculation rate of 600 $L \cdot h^{-1}$. The water enters each compartment various times before leaving the MBR as purified permeate with a total residence time of 5.6 and 3.52 h for the aerobic and anoxic compartments.

The permeability of module 1 significantly dropped on day 41 to around 100 $L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$ and the TMP or suction pressure fluctuated around 180 mbar (see Figure 2, top). Permeability and TMP remained at this level for the following 50 days until module replacement. The permeability of module 2 dropped within the first 12 days to below

$100 \, L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$. Prior to the pilot trials, permeate pump 1 had a breakdown due to damage in the turbine blade wheel. As a consequence, the biofilm layer on the membrane surface could build up, which could cause a rapid TMP increase, reducing the permeability significantly. After the TMP peak on day 26, the flux and thus the HRT was reduced to avoid further impairing the membrane. Because MARTIN Systems recommended conducting chemical membrane cleaning below $100 \, L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$, module 2 was cleaned ex situ with a 1% hypochlorite solution for biofouling removal. After cleaning, it regained permeability (day 33) and eventually dropped to 150 to $200 \, L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$ at TMP around 80 to 160 mbar.

Subsequently, the PBM-coated membranes (now denoted as "module 1") replaced the commercial module 1 on day 91. Trials to compare both modules started and continued until day 160 (Figure 2, top). As was expected, the permeability of module 1 (with PBM coating) was significantly lower compared to the commercial one because the PBM layer adds additional resistance for the water to pass the physical barrier. In the course of the pilot trials, the permeability for the PBM module remained constant, whereas the TMP increased with a gradient of 1 mbar/d. This is a strong indication that the PBM coating is not washed off over time, which is important when testing novel membrane coatings. The specific pressure increase for the commercial PES (module 2) membrane module was noticeably lower with around $0.4 \, mbar \cdot day^{-1}$. The maximum operation time for the PBM membrane module was 69 days in total (Figure 2, top). A moderate cleaning interval using 500 ppm sodium hypochlorite (NaOCl) was carried out in order to remove a minor biofouling layer.

Membrane performance was also studied using flux step tests, based on the work of Monclús et al. (2011) and Le Clech et al. (2003). Prior to the tests, both modules were slowly adapted to enable pore swelling. Following a 30 min relaxation phase, the flux step test started at 5 LMH for both membrane modules, and the flux was then gradually increased by 5 LMH up to 50 LMH. Each gradual increment consisted of 2 permeation and 2 relaxation cycles of 12 min and 3 min, respectively. Transmembrane pressure was continuously recorded and the specific pressure increase calculated by the equation

$$\frac{dTMP}{dt} = \frac{dTMP_n - dTMP_{n-1}}{dt},$$

as depicted in Table 2 (bottom, left), wherein d, t, and n refer to the derivative of transmembrane pressure with respect to time, in steps n. The procedure is valid for the entire test range, up to 50 LMH. Accordingly, average specific pressure increase for each incremental flux is also shown in Figure 2 (bottom, right). The MLSS was around $6 \, g \cdot L^{-1}$. Flux step tests were reproduced after an extensive

Table 2. Water quality of permeate samples

Parameter	Unit	SD of method	8 Feb 2019 Commercial membrane module 1[b]	22 May 2019 Commercial membrane module	22 May 2019 PBM-modified membrane module
pH	pH scale	±0.1	7.8	7.9	7.9
Electrical conductivity	$\mu S \cdot cm^{-1}$	±10	762	654	654
COD	$mg \cdot L^{-1}$	±4.9	75	68	70
TOC	$mg \cdot L^{-1}$	±0.5	15.9	4.5	5.7
TIC	$mg \cdot L^{-1}$	±0.5	31.8	15.7	16.3
NH_4^+	$mg \cdot L^{-1}$	±0.0138	0.16[a, c]	0.111[a]	0.075[a]
NO_3^-	$mg \cdot L^{-1}$	±0.8	88.6	117.7	116.5
TN	$mg \cdot L^{-1}$	±1.0	25.0	33.7	32.2
PO_4^{3-}	$mg \cdot L^{-1}$	±0.1	13.0	11.9	13.1
SO_4^{2-}	$mg \cdot L^{-1}$	±0.8	65.2	69	76.5
Cl^-	$mg \cdot L^{-1}$	±0.5	171.3	73.6	74.2
Na^+	$mg \cdot L^{-1}$	±0.1	84.2	83.9	85.4
K^+	$mg \cdot L^{-1}$	±0.1	75.5	31.5	32.6
Mg^{2+}	$mg \cdot L^{-1}$	±0.5	19.8	14.0	12.9
Ca^{2+}	$mg \cdot L^{-1}$	±0.5	45.4	52.6	54.2

PBM = polymerizable bicontinuous microemulsion; COD = chemical oxygen demand; TOC = total organic carbon; TIC = total inorganic carbon; TN = total N.
[a]Cell test Merck KGaA 1.14739.0001.
[b]Commercial membrane module 2 not analyzed.
[c]Value measured at pilot plant, Kisumu, Kenya.

in-situ cleaning using NaOCl, sodium hydroxide (NaOH), and citric acid. Sodium hypochlorite is a common chemical used to clean MBR membranes, and the sludge inside the filtration compartment was pumped into a separate buffer tank prior to the in-situ cleaning. Afterwards, the filtration compartment was rinsed with clean water to avoid any negative effect on the microorganisms when refilling with the buffered sludge.

It can be seen that the PBM could not achieve competitive performance throughout the flux step test (Figure 2, bottom, light red curve). It is striking that the specific pressure increase is higher during the first flux step tests for both membranes. This could be due to very high stress on the membrane caused by the high-volume flow rates and the resulting noticeable expansion of the membrane pores. According to pertinent literature, membrane aging is influenced by the filtration conditions and the frequency and strength of chemical membrane cleaning (Yoon 2016). This change in the microscopic membrane texture ultimately leads to a membrane replacement. A qualitative chemical resistance of the PBM layer was confirmed through extensive lab-scale tests and Fourier-transform infrared spectroscopy (FTIR) measurements subsequent to the pilot field trials. For a quantitative statement about leaching of the PBM, however, further long-term studies are required.

In summary, it is important to mention that the domestic wastewater used generally exhibits very low fouling propensity for the commercial PES membrane, meaning that the PBM coating cannot harness its full potential. The PBM membrane modification is based on the polymerization of different monomers forming a strong covalent polymer. The incorporated AUTEAB surfactant involves an antimicrobial active cationic quaternary ammonium salt group (Mancuso et al. 2017). The cosurfactant HEMA improved the hydrophilicity of the membrane coating layer, validated by contact angle measurements (CAMs). Lastly, the PBM layer reduced the membrane surface roughness and thus the potential attachment of colloids and biomass (Galiano et al. 2015). For domestic wastewater treatment, the advantage in terms of fouling reduction cannot compensate for the disadvantage of the higher flow resistance through the applied coating. However, it is expected that the PBM coating would achieve better performance at high-strength water pollution having higher fouling propensity, as previously demonstrated by treating, for example, textile wastewater (Deowan et al. 2016). Therefore, it was assumed that PBM membrane could not fully deploy its potential for low-strength domestic wastewater filtration.

Chemical O demand, N, P removal efficiency

Figure 3 depicts COD in the MBR feed, COD in permeate (module 1, only), and COD removal efficiency during operation period 1 (2 commercial modules). The feed COD fluctuates between approximately 200 and 800 mg $\cdot$ L^{-1} and lies in the typical range of domestic wastewater. The COD in permeate is typically <100 mg $\cdot$ L^{-1} (mean 60 mg $\cdot$ L^{-1}), resulting in overall COD removal efficiency >80%. The HRT

based on total MBR volume of 1.7 m^3 (3 compartments) was reduced from 21 h (13 LMH) to 13.5 h (20 LMH). The MLSSs fluctuated between 5 and 11 g $\cdot$ L^{-1}. Based on a survey among MBR users in 2016, MLSS typically ranges from 6 to 12 g $\cdot$ L^{-1} with a mean concentration of between 8.2 and 8.8 g $\cdot$ L^{-1} (MBR site 2019). During operation period 2, starting on day 91 (commercial + PBM module in parallel), COD quality is similar in the permeate of both modules.

Ammonium is a critical parameter for fish in aquaculture due to its toxicity. Elevated ammonium displaces K$^+$ and can eventually cause cell death in the central nervous system (Randall and Tsui 2002). It is therefore recommended that the total ammonium level in aquaculture be kept below 1.5 mg $\cdot$ L^{-1}.

As Figure 3 shows, ammonium in the feed is significantly lower than the values given in Table 1, which can be explained by the additional discharge of wastewater from lorries into the WSP (see *Materials and Methods* and *Wastewater quality* sections). Hence, the wastewater quality can vary greatly. This fact is supported by a wastewater analysis from the Nyalenda pond influent carried out in 2017 at Karlsruhe University of Applied Sciences showing ammonium concentration of only 6.9 mg $\cdot$ L^{-1}. Ammonium in the permeate was below 0.5 mg $\cdot$ L^{-1} before day 41, indicating high nitrification rates. At day 43, a sudden jump to 4 mg $\cdot$ L^{-1} was noticed, which could be explained by a technical issue in the wastewater feed.

Due to a clogged cartridge prefilter, the wastewater tank could not be refilled, and subsequently, the MBR water level in the reactor dropped to 50%, which caused a problem with the nitrification (lower DO mass transfer due to higher MLSS concentration). With this technical issue resolved, the nitrification rate regained and consequently the ammonium in permeate dropped below 0.5 mg $\cdot$ L^{-1} (day 45). During operation, the ammonium values were similar in the permeate of the commercial module and PBM module, not showing critical values for the reuse inside the RAS. Nitrate is less critical with regard to fish toxicity. However, at elevated nitrate concentration, reduced growth and impaired health status of fish can be noticed (Monsees et al. 2017). Therefore Monsees et al. (2017) recommend not exceeding concentrations of 500 mg $\cdot$ L^{-1} NO$_3$–N in juvenile tilapia culture to ensure an optimal health and growth status of the fish because below that concentration they observed no effects on the tilapia.

Initially, nitrate level in the permeate (module 1) ranged between 100 and 140 mg $\cdot$ L^{-1}. On day 26, a significant drop occurred because of an interruption in aeration inside the nitrification chamber caused by a technical failure of the blower and the consequent anoxic conditions. The denitrification rate was therefore enhanced. High levels of DO impair the anoxic conversion of nitrate into N$_2$. For DO levels >0.2 mg $\cdot$ L^{-1} (Hanhan et al. 2011), bacteria uses molecular O for the metabolism despite the bound O in the nitrate. The DO should therefore be kept at a minimum inside the anoxic compartment. Substantially high ammonium levels and insufficient aeration inside the nitrification

compartment hamper the conversion into nitrate. Accordingly, anoxic processes producing N_2 are reduced. Therefore aeration was optimized and nitrate concentration decreased below $10\,mg \cdot L^{-1}$ inside the nitrification tank. Dissolved O inside the denitrification compartment was always below $0.2\,mg \cdot L^{-1}$. In addition, on days 70 and 130, lack of nitrification and spiking ammonium also contributed to lower nitrate levels (see Figure 3). There appears to be room for further optimization of nitrate removal, for example, by reducing the recirculation rate into the denitrification compartment.

Orthophosphate (PO_4^{3-}) has no toxic effect on fish but causes eutrophication, which leads to algae growth in the RAS system or generally in the environment (Effendi et al. 2018). Orthophosphate is reduced from 40 to $90\,mg \cdot L^{-1}$ in the feed of MBR to 10 to $30\,mg \cdot L^{-1}$ in the permeate (module 1) during operation phase 1. Within phase 2 it can be noticed that phosphate removal was roughly similar for the PES and PBM modules and the phosphate level was constantly below $10\,mg \cdot L^{-1}$. Mburu et al. (2019) have demonstrated on ortho pilot scale that orthophosphate can be further reduced by adding $Al_2(SO_4)_3$ as a chemical coagulant into the MBR tank.

Permeate water quality

During the pilot trials, several full analyses of permeate water were carried out and then compared to the required standards for aquaculture and irrigation.

Table 2 gives the full analysis of the permeate sample during operation period 1 on 8 February 2019 (commercial module 1) and operation period 2 on 22 May 2019 (commercial module 1 and PBM-modified module 2). It also shows that the permeate quality of the commercial module during operation phases 1 and 2 is similar. Within phase 2, the water quality of the modified PBM module 1 hardly differs from the commercial one.

On 27 February 2019, permeate sample of module 1 was sent to the official analytical laboratory Water Resources Management Authority (WARMA, Kisumu) for the water quality to be checked against the standards of the Food and Agriculture Organization of the United Nations (FAO) for irrigation and aquaculture (Bregnballe 2015). As shown in Supplemental Data Table S-1, all parameters were in agreement with the standards with the exception of total P in aquaculture. Although not toxic for fish, it does however contribute to eutrophication, as mentioned in the *Chemical O demand, N, P removal efficiency* section. Through PBM coating, the MWCO of the membrane was reduced (Galiano 2013). However, the PBM-treated membrane is still a (denser) UF membrane, and small dissolved organics and salts can pass. Contrary to received wisdom, pertinent literature confirmed that lower MWCO does not necessarily increase the removal efficiency even for smaller particulates (Yoon 2016). This was also confirmed by the permeate water analysis for PBM and PES membranes, which shows that all the parameters of PBM and commercial PES membrane were comparable (Table 2). Slight deviations lay mostly within given measuring errors. For multivalent and monovalent ions, the lower MWCO through PBM coating is still above the value for significant removal that could be achieved only by nanofiltration membranes.

Furthermore, Technologie Zentrum Wasser (TZW; German Water Centre), Karlsruhe, analyzed some permeate samples for a variety of metals. As shown in Table 3, all analyzed metal concentrations are very low, which is in agreement with the findings of WARMA (Supplemental Data Table S-1). Despite levels of Cu and Zn, there were no metals detected in the raw sewage (see Table 3). Studies have shown that metals are accumulated in the sludge, depending on MLSS level (Aréalo et al. 2013). Therefore, the metal removal for Cu and Zn is not achieved through the filtration but through sludge accumulation. Ciprofloxacin came into widespread use in Africa in the early 2000s and is known to be poorly biodegraded during wastewater treatment (Nguyen et al. 2018). It is adsorbed mainly by the activated sludge, and because the adsorption capacity of the sludge is limited, it can pass the membrane. Other antibiotics are known to be more biodegradable (e.g., sulfamethazine; Perez et al. 2005) and were below the detection limit (BDL). As shown in Table 3, the concentration of Metronidazol is rather low. It is BDL in raw sewage and feed and is only slightly above detection limit (DL) in the permeate.

Additionally, the permeate was tested on selected antibiotics typically used at household level in Africa, eventually entering the domestic wastewater that is fed to the pilot MBR (see Table 3). Antibiotics in wastewater are of concern because they show low biodegradability in common sewage treatment plants and they can accumulate in the tissue of animals or plants. Widespread use of antibiotics may lead to the development of resistant human pathogens (Canada-Canada et al. 2009). The following antibiotics were analyzed: Amoxicillin, Cloxacillin, Dicloxacillin, Nafcillin, Oxacillin, Penicillin G, Penicillin V, Metronidazol, and Ciprofloxacin. Only Metronidazol and Ciprofloxacin showed values above the DL. Metronidazol occurred in only 2 samples slightly above DL, whereas Ciprofloxacin concentration was considerably higher. However, Ciprofloxacin was significantly reduced in the permeate samples (particularly in PBM permeate). The amount taken up by fish in aquaculture remains unclear and will be investigated later. If needed, Ciprofloxacin could be further removed be adding a simple activated C filter downstream of MBR. Based on a study by Baresel et al. (2017), Ciprofloxacin can be removed >80% by use of granular or powdered activated C.

Specific energy demand

Load power fluctuates in the operation mode of the MBR due to discontinuous operation scenarios. Controlled by the programmable logic controller (PLC) unit (Siemens CPU 1510SP-1 PN), the MBR runs fully automated, balancing out the system based on the water levels inside the separate MBR compartments defined by the user inputs. On average, the MBR power consumption is calculated to $4\,kWh \cdot m^{-3}$ at a nominal power of $498\,W_{el}$ with peak values of up to $861\,W_{el}$.

Table 3. Permeate analysis on metals and antibiotics

Sample date	Sample from	Cd (mg·L^{-1}) (DL = 0.0001)	Cu (mg·L^{-1}) (DL = 0.01)	Zn (mg·L^{-1}) (DL = 0.02)	Pb (mg·L^{-1}) (DL = 0.001)	Hg (mg·L^{-1}) (DL = 0.00005)
8 Feb 2019	Intake tank	0.0001	0.07	0.29	0.006	<BDL
8 Feb 2019	Permeate commercial PES Module 1	<BDL	<BDL	0.03	<BDL	<BDL
8 Feb 2019	Permeate commercial PES Module 2	<BDL	0.02	0.04	<BDL	<BDL
8 Feb 2019	Nitrification tank	<BDL	0.02	0.02	<BDL	<BDL
24 Apr 2019	Raw sewage	<BDL	0.02	0.07	0.005	<BDL
24 Apr 2019	MBR feed	<BDL	0.07	0.06	0.002	0.000057
24 Apr 2019	Permeate coated PBM module	<BDL	0.02	0.06	<BDL	<BDL
24 Apr 2019	Permeate commercial PES module	<BDL	0.02	0.06	<BDL	<BDL

Sample date	Sample from	Ciprofloxacin (ng·L^{-1}) (DL = 100 ng·L^{-1}, SD = 9.5 ng·L^{-1})	Metronidazol (ng·L^{-1}) (DL = 50 ng·L^{-1}, SD = 13.8 ng·L^{-1}
8 Feb 2019	Nitrification tank	710	<BDL
8 Feb 2019	Permeate commercial PES Module 1	820	<BDL
8 Feb 2019	Permeate commercial PES Module 2	790	<BDL
24 Apr 2019	Raw sewage	1430	<BDL
24 Apr 2019	MBR Feed	980	<BDL
24 Apr 2019	Permeate coated PBM module	640	66
24 Apr 2019	Permeate commercial PES module	790	67

BDL = below detection limit; DL = detection limit; MBR = membrane bioreactor; PBM = polymerizable bicontinuous microemulsion; PES = polyethersulfone.

However, the intake tank pumping the raw sewage into the system is not considered because this factor varies greatly depending on the application (type of wastewater and location). Also, in some cases the intake pump could be entirely excluded when geodetic heights are used. It should be noted that the pilot MBR contains a second permeate line (additional pump), which is not required for common operation. Specific energy consumption is correspondingly lower for operating 1 module with respect to the pilot MBR in Kisumu.

According to a current review (Krzeminski et al. 2017), the energy demand for full-scale MBRs is around 0.4 to 1.6 kWh·m^{-3}, which is significantly lower than for the pilot MBR. However, the specific energy demand system decreases at a rate inversely proportional to the installed capacity (Gu et al. 2017) due to higher efficiency of pumps and aerators. Given that the pilot MBR is an experimental, small-scale system with a 3 m^3 daily capacity, the specific energy demand appears realistic.

DESIGN OF LOW-COST MBR

The fully automated pilot MBR includes various functions and operative scenarios that incur high capital costs. Very simplified small-scale MBRs ranging from 0.8 to 8.3 m^3·d^{-1} are available, but costs increase substantially due to costs

associated with importation and shipping into the region. Therefore, a low-cost MBR should be reduced to its minimum functions and designed with materials available locally on the market.

Simple manually operated valves, on/off switches, and geodetic heights could replace automatic system functions. More specifically, the size of recirculation pumps can be reduced when running continuously, which has a positive effect on the capital cost. Simple float switches can further replace level (pressure) sensors. In general, sensors, including acquisition and PLC system-controlling pumps and switches, can be removed completely without negatively impairing the filtration process or reducing the water quality achieved. Nevertheless, the training of employees then becomes even more important, which in turn also creates new job opportunities. Current calculations have shown that with this approach of using mainly local products, a MBR of a 10 m^3 capacity per day can be achieved with a €6000 investment, depending on location and inlet conditions. Operation costs can be estimated at about €1000/y.

Ultimately, a simplified system reduces capital and operational costs significantly but also improves operational stability, leading to lower maintenance, operating, and also personnel costs. Power consumption for an upscaled MBR

system could be lowered from 4 to 1.9 kWh · m^{-3} due to the higher efficiency of bigger pumps and adapted blowers. The second permeate pump was excluded and the controlling reduced to the most essential functions. Mechanical float switches replaced leveling with pressure sensors. Electricity costs for Kenya were assumed at €0.15/kWh and the depreciation calculated at 10 y. Without major maintenance (membrane replacement), the specific cost for 1 m^3 of treated wastewater was calculated to €0.52 and includes the specific energy consumption and consumables such as chemicals for periodic membrane cleaning as well as basic water analysis. Currently, Karlsruhe University of Applied Sciences works on the implementation of a low-cost MBR for treating hospital wastewater in Kampala, Uganda. The potential for such systems in the Eastern African region is consistently high. After demonstrating the technical feasibility within the present study, the coming project will validate the economic viability to further raise the acceptance of MBR for water reuse.

POTENTIAL APPLICATIONS OF MBRs IN FISH PROCESSING INDUSTRY IN THE LAKE VICTORIA REGION

A study of functional fish processing plants (FPPs) in the Lake Victoria Basin (LVB), in relation to wastewater management and MBR, affirmed that most industrial fish processing generates potentially large quantities of solid waste and byproducts and wastewater residues of high organic content which, if not properly recycled or treated, cause environmental threats. The FPP wastewaters have a high organic content, and subsequently a high BOD, because of the presence of byproducts such as blood, scales, offal, tissue, and dissolved protein, together with inorganic compounds from detergents and disinfectants (applied during facility cleaning activities). A detailed analysis of average parameters for FPP discharge can be found in Supplemental Data Table S-2. On average the FPPs in the LVB use up to 70 378 m^3 of water per day. The FPPs require 20 m^3 · t^{-1} of fillet produced (Gumisiriza et al. 2009) and mains water is primarily consumed for washing and cleaning purposes, as media for storage and refrigeration of fish products and for machine cooling. Due to the fraught situation of clean water access in the LVB, MBR is a beneficial application for the fish processing industry (FPI).

For instance, a high treatment efficiency (Jemli et al. 2015; Mburu et al. 2019) can be achieved because the wastewater of the FPI is highly biodegradable. The quality of MBR-treated water (e.g., high germ removal rate) is adequate for direct reuse in the process, for example, for washing purposes or irrigation (Jemli et al. 2015; Mburu et al. 2019). The wastewater of the FPI is generally very rich in N, and MBRs have a high degree of denitrification due to the high sludge age in combination with an installed upfront anoxic tank. Additionally, P removal can be easily integrated through phosphate precipitation, which is retained by the membranes. Finally MBRs are highly robust, run with low maintenance and could be easily addressed to the FPI with particularly high fluctuating organic load rates.

Though 93% of the responding fish processors in the LVB had never heard of MBR technology, 87% were willing to adopt MBR because of the rapid urbanization of surrounding land for discharge, the low footprint of MBR, and the increasing desire to reduce production costs. In addition, MBR technology has the advantage of reusing treated water in the production process, which contributes to saving fresh water and further reduces costs.

DISCUSSION AND CONCLUSION

In conclusion, the present study validated the possibility of using MBR technology for reusing domestic wastewater in aquaculture and irrigation. The small-scale MBR plant with submerged commercial PES membranes can be operated smoothly and provides treated water in basic agreement with the given FAO standards. Within this project, MBR-treated wastewater (3–4 m^3 · d^{-1}) could be used to replace water loss in an RAS for breeding tilapia fingerlings without showing adverse effects to the fish. In terms of critical trace elements such as metals and antibiotics, only Ciprofloxacin occurs in concentrations significantly above DLs, despite a 50% removal efficiency. However, potential accumulation in fish still needs to be studied.

A novel developed membrane module with PBM-based low-fouling coating runs stably, but it did not improve the filtration performance compared to the commercial one. It was assumed that the PBM coating is less suitable for low-strength domestic wastewater. The membrane modification with PBM coating showed an improved critical flux in previous studies treating high-strength textile wastewater (Deowan et al. 2016), thanks to a higher antimicrobial activity, reduced surface roughness, and a higher hydrophilicity achieved. An advanced coating technique to improve the PBM coating is being studied in an ongoing laboratory work. The technology reduces the pore intrusion of the liquid PBM into the porous PES membrane, offering the possibility of a well-defined and very thin coating layer.

In general, MBR technology shows promising applications not only in RAS but also in FPPs in the LVB (Mburu et al. 2019). However, some emerging questions require further studies. For instance, the quality of MBR-treated wastewater as well as the quality of fish, particularly regarding micropollutants such as antibiotics, should be the focus of upcoming projects. In addition, the overall removal efficiency of N and P by denitrification and precipitation, respectively, in the MBR tank should be improved. Finally efforts should be put on investigating the long-term performance of the novel PBM low-fouling membrane coating versus the commercial ones for treating high-strength wastewater.

Zentrum Wasser (Karlsruhe) for conducting analysis on metals and antibiotics.

Open Data Badge—This article has earned an Open Data Badge for making publicly available the digitally shareable data necessary to reproduce the reported results. The data are available at https://figshare.com/authors/Jan_Hoinkis/8719386. Learn more about the Open Practices badges from the Center for Open Science: https://osf.io/tvyxz/wiki.

Data Availability Statement—The data used in this study are publicly available at https://figshare.com/authors/Jan_Hoinkis/8719386.

SUPPLEMENTAL DATA

Figure S-1. Approach of VicInAqua Project.
Table S-1. Water quality of permeate samples
Table S-2. Average biochemical parameters

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