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Demonstration of Wastewater Recycling in a Slaughterhouse

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Featured Application: Slaughterhouse wastewater recycling using a combined process consisting of flotation, membrane bioreactor, and reverse osmosis.

Abstract: The implementation of research results in industrial applications is a crucial step in the development of innovative technologies. In this work, slaughterhouse wastewater recycling was successfully realized. The system, comprising a process combination of flotation, membrane bioreactor, and reverse osmosis, was able to treat the wastewater from a medium-sized poultry slaughterhouse in northwestern Tunisia. The process managed to treat approximately one-third of the wastewater to the required standard for agricultural irrigation. An additional 35% was purified to drinking-water quality. The remaining water was discharged as concentrate, meeting the necessary limits for indirect discharge. As a result, the slaughterhouse's fresh water consumption was reduced by 35% and the amount of wastewater by around 70%. With the combined system, average reductions of 99%, 98%, and 96% were achieved for the parameters COD, TN, and electrical conductivity, respectively.

Keywords: wastewater recycling; slaughterhouse wastewater; demonstration plant; membrane separation technology; reverse osmosis; ultrafiltration; membrane bioreactor

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1. Introduction

In times of increasing freshwater scarcity [1], the management of wastewater is gaining importance [2]. A compilation of United Nations data on global municipal wastewater treatment shows that 60% of wastewater is treated, 40% is indirectly reused (unplanned or planned), while only 5% is directly reused [3]. Globally, 72% of all water withdrawal is for agriculture, 16% by municipalities for households and services, and 12% by industry. However, these shares shift towards industrial water demand as the degree of industrialization of a country increases [4]. Nevertheless, the direct reuse of water is only possible for municipal wastewater for households and services as well as for industrial wastewater. In the case of industrial wastewater, the challenge comes from very different wastewater compositions and degrees of pollution. Consequently, the implementation of a wastewater reuse system requires a high degree of innovative approaches. Looking at the four phases of the linear innovation process (discovery, invention, development, and diffusion), it is noticeable that scientific publications primarily focus on the first two phases: discovery and invention [5]. Slaughterhouses are significant contributors to water pollution, particularly in developing countries, as their wastewater contains high concentrations of organic matter, nutrients, and pathogens, leading to oxygen depletion, eutrophication, and public health concerns [6]. In the case of slaughterhouse wastewater (SWW) reuse, there are a number of publications on these two phases [7–15], as well as an article on the development phase [16]. This article aims to expand on this with a further case study on the next phase of 'development'. The majority of slaughterhouses treat their wastewater using flotation systems before discharging the pretreated water to municipal wastewater treatment plants [17–19]. Larger slaughterhouses may implement additional on-site treatment processes, such as activated sludge or a combination of anaerobic and aerobic biological processes, to meet the requirements for discharging into local water bodies [20]. However, the direct recycling of SWW has not yet been explored in practice. This study addresses this gap by investigating the feasibility of direct SWW recycling as a novel approach. A process previously tested in the laboratory at bench scale was implemented in a Tunisian slaughterhouse, with an SWW effluent of about 55 $m^3 \cdot d^{-1}$.

It is a medium-sized industrial slaughterhouse in the north-west of Tunisia. An average of 4000 to 8000 chickens are slaughtered per day, 6 days a week. Turkeys are slaughtered only occasionally. The site already operated an SWW treatment system consisting of screens, a gravitational flotation system, and a cascade-type aeration basin system without sludge recirculation. Based on preliminary testing, a concept was developed to implement an SWW recycling system using the existing equipment. This was then constructed by the company Delta Umwelt-Technik GmbH, Teltow, Germany, in the form of a container plant. The existing activated sludge system was optimized. Three MESSNER®, Adelsdorf, Germany, compact plate diffusers were installed and the old blower was replaced by a KDT 3.80 rotary vane compressor from Becker GmbH, Wuppertal, Germany.

This article presents the process of implementation from planning to steady-state operation. Not only is the process of the implementation of the SWW recycling system considered, but also the transfer of research results from the laboratory to industrial application.

2. Materials and Methods

2.1. Slaughter Process at the Site

According to the slaughterhouse's information, the slaughter quantity was around 6000 chickens per day during the data collection period, but this figure fluctuated by up to 2000 per day depending on market demand. The slaughter process in a commercial chicken slaughterhouse involves several steps to ensure hygiene, efficiency, and compliance with regulations. Figure 1 provides an overview of the steps performed in the chicken slaughterhouse, as well as the resulting residues.

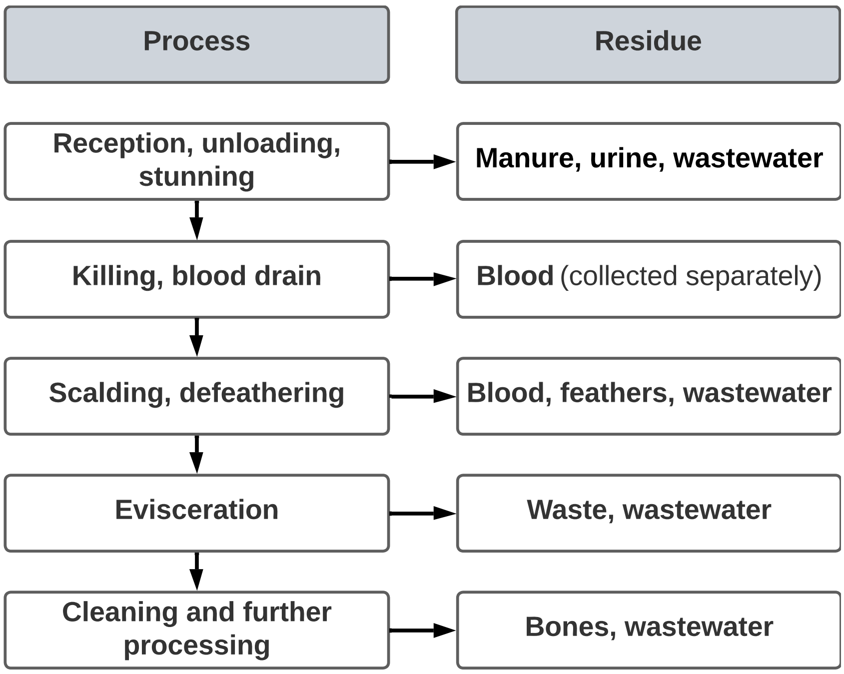

Figure 1. Slaughter process.

2.2. Existing Wastewater Treatment System

The wastewater concept of the slaughterhouse at the site starts with the collection of SWW from the various process steps in troughs. It should be noted that the blood, after decapitation of the animals, is collected in a separate gutter, and all the blood is diverted, independently of the rest of the SWW system, into a tank and is externally valorized. Apart from this, the collected SWW flows to an onsite SWW treatment plant. The process flow diagram of the SWW treatment plant before the implementation of the demonstration plant is shown in Figure 2. Photos of the wastewater system can also be viewed in Figures A1 and A2.

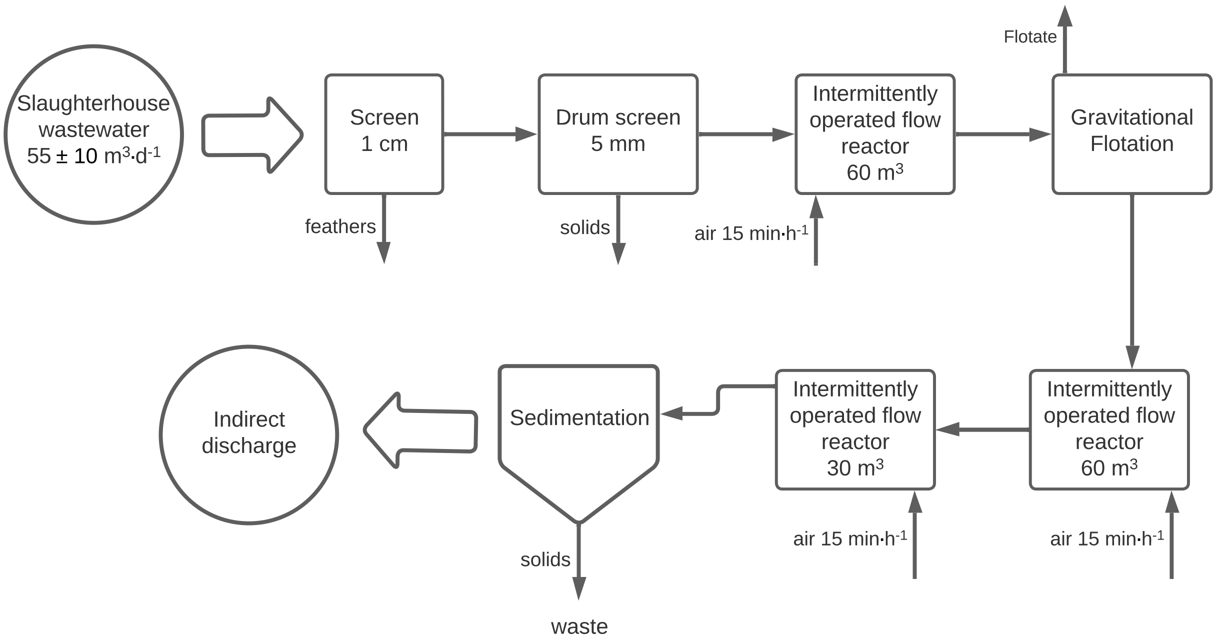

Figure 2. Process sequence before implementation of the demonstration plant.

The slaughterhouse operates 6 days per week and produces approximately 55 $m^3 \cdot d^{-1}$ of SWW with daily fluctuations. The plant has three basins connected by overflow, the first two with a capacity of 60 m^3 and one with a capacity of 30 m^3. Only one of the large basins was used at that time. The treatment process starts with a coarse sieve with a hole size of 1 cm to separate the feathers, followed by a drum sieve with a hole size of 5 mm. This is followed by the first biological stage in the form of an intermittently operated flow reactor with 15 min of aeration per hour. A pump transports the water from there to the gravitational flotation, where the suspended fats are removed. This is followed by the smaller intermittently operated flow reactor with the same aeration interval, which drains with an overflow. Finally, the remaining solids are removed in a sedimentation tank, and the overflow is released as an indirect discharge to the sewer and to the municipal wastewater treatment plant. There, the limit value of 1 $gCOD \cdot L^{-1}$ has to be met. All solid waste is disposed of via a third-party provider.

2.3. Wastewater Recycling Process

For the implementation of the SWW recycling system, efforts were made to continue using as many of the existing plant elements as possible. Figure 3 shows the modified process flowsheet, with the added process sections highlighted in red. In addition to the added process steps, some components were changed in their utilization. The first intermittently operated flow reactor was converted into a mixing and equalization basin. The gravitational flotation was upgraded with a microbubble generator to dissolved air flotation without chemical flocculation. The former second intermittently operated flow reactor was converted, by using ultrafiltration (UF), into a membrane bioreactor (MBR) with sidestream cross-flow membrane filtration. Finally, a reverse osmosis (RO) system was integrated as the last process step to achieve treatment up to process-water quality. The combination of processes makes it possible to produce water of different quality levels according to requirements. Thus, the effluent of the MBR can already be used for agricultural irrigation.

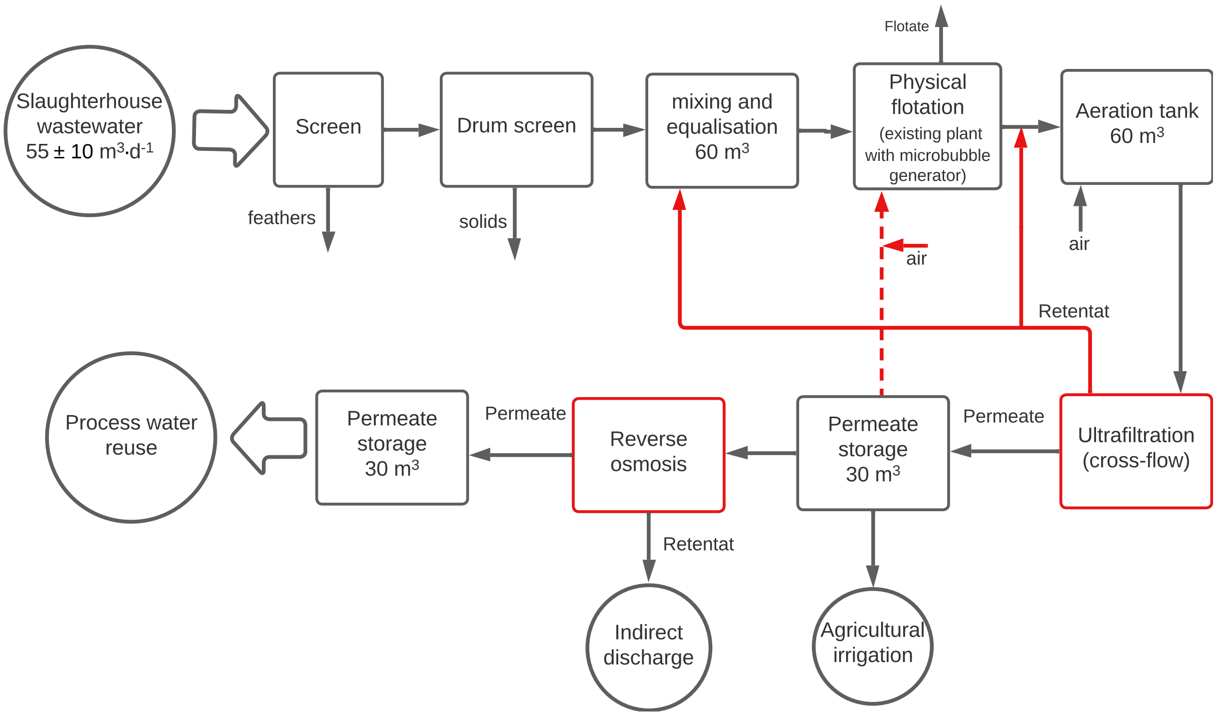

Figure 3. Slaughterhouse wastewater recycling concept: red symbolizes the newly added system parts; dashed line symbolizes a pressure line that is not connected to the retentate line.

2.4. Process Description

In order to provide a better overview over the whole system, the process is subdivided for a more detailed description as follows:

- Pretreatment via physical flotation;
- Biological treatment via membrane bioreactor;
- Polishing via reverse osmosis.

As before the modification, all solid waste is disposed of via a third-party provider. The complete flow diagram of the process is shown in Figure A3, and a photo of the container system is shown in Figure A4. The individual sections are examined in more detail below.

2.4.1. Physical Flotation

In the first process step, fats and suspended solids are separated from the SWW by means of flotation. The SWW is pumped from the mixing and equalization tank into the flotation tank, which has a surface area of 2 m^2, using a submersible pump. The solids are removed on the surface using a skimmer. The cleaned SWW is drawn off below the water surface and fed into the MBR. In addition, recirculation water is supersaturated with air at 4–5 bar in a pressurized tank and released into the wastewater stream via a tension valve. The resulting microbubbles cause the suspended solids in the water to float to the surface, where they can be separated. The UF permeate was used as the recirculation water to avoid blockage in the pressure vessel. The simplified flotation flow diagram is shown in Figure 4.

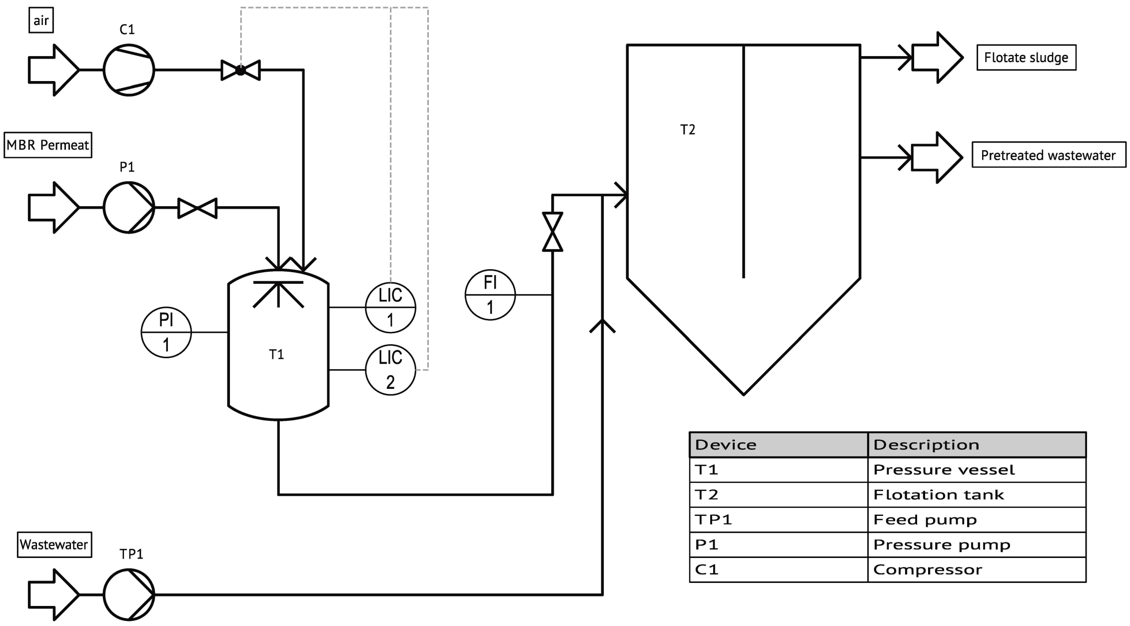

Figure 4. Simplified process flow diagram of the physical flotation.

2.4.2. Membrane Bioreactor

The MBR system consists of an aeration tank with a base area of 16 m^2 and a maximum volume of 65 m^3. Three MESSNER® "Compact Aeration Panels" with a surface area of 1 m^2 each are installed at the bottom of the tank. The plates have an airflow range of 0–30 m^3_N ·h^{-1}. A photo of the plates after installation is shown in Figure A5. The air is supplied by a KDT 3.80 rotary vane compressor made by Gebr. Becker GmbH (Wuppertal, Germany). The system is supplemented with a sidestream UF cross-flow membrane system. This consists of two tubular modules of "T-CUT UF 100-080 PVDF 159-3000 Steel" from WTA UNISOL GmbH, Gotha, Germany. The membrane modules have a molecular separation size of 100 kDa and a membrane area per module of 15 m^2. The modules can be operated up to a maximum pressure of 10 bar and are installed in an 8″ stainless-steel tube with a total length of 3 m. Figure 5 shows the system as a simplified flow diagram. Due to the cross-flow design, the retentate can be returned to the aeration tank for biomass enrichment or to the mixing and equalization tank, where the solids are removed as flotate.

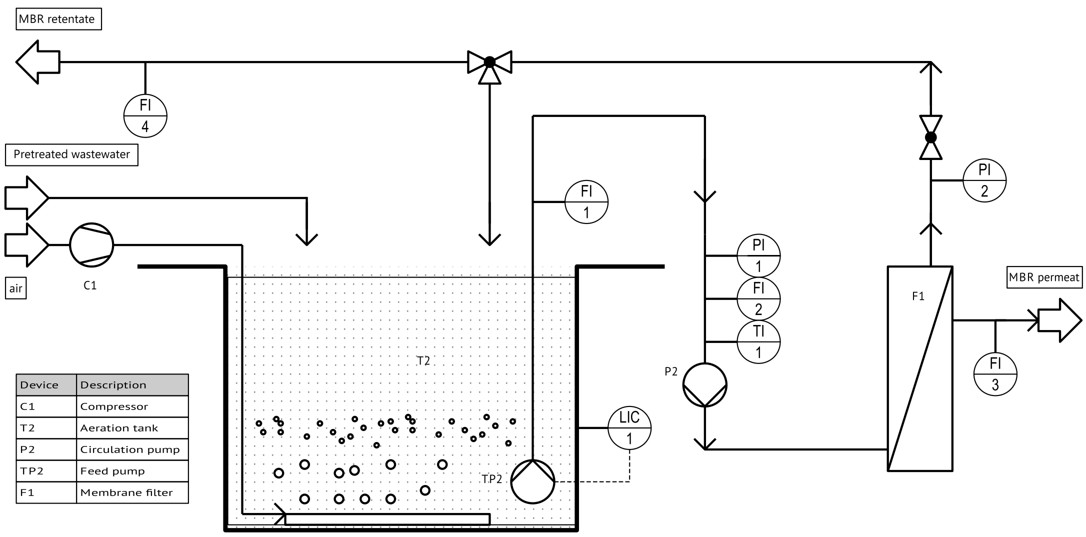

Figure 5. Simplified process flow diagram of the membrane bioreactor with sidestream ultrafiltration.

2.4.3. Reverse Osmosis

The last treatment step is an RO system. This consists of 4 pressure pipes in a 2:1:1 cascade circuit in which two BW 30-4040 spiral modules are installed. The spiral modules consist of a polyamide thin-film composite membrane and each have an active membrane area of 7.2 m^2. A maximum transmembrane pressure (TMP) of 13 bar can be achieved in the system and the system is designed for an average water yield of 60%. The permeate from the MBR system is transported to the RO system using a submersible pump; the required TMP is generated in the system using the MovitecVSF004/20-B1P14ES013025VW pump from KSB SE & Co. KGaA (Berlin, Germany). A simplified flow diagram of the RO system is shown in Figure 6.

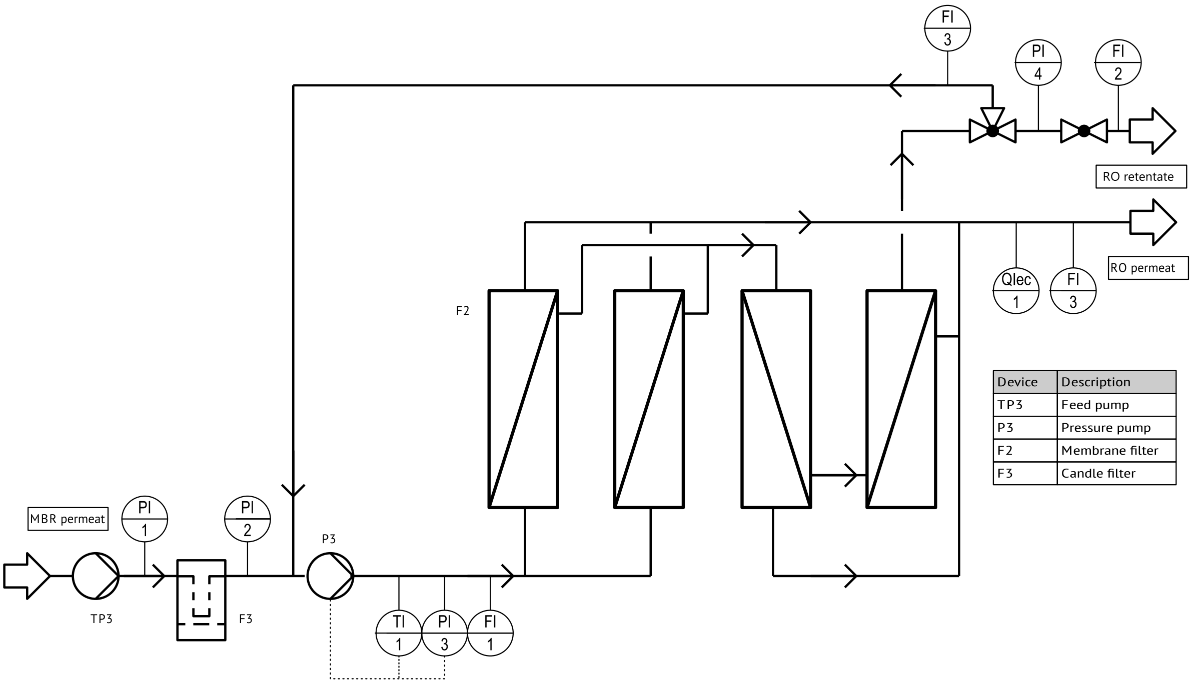

Figure 6. Simplified process flow diagram of the reverse osmosis.

2.5. Analytical Methods

Various parameters were continuously monitored and analyzed to assess the efficiency of the SWW recycling process. Notably, pH values, electrical conductivity, chemical oxygen demand (COD), total organic carbon (TOC), total nitrogen (TN), total solids (TS), total suspended solids (TSS), sludge volume (SV), and a selection of free cations and anions were monitored to assess the effectiveness of the treatment.

The pH value was determined with a FiveEasy^{TM} FE20 pH meter from Mettler-Toledo AG (Schwarzenbach, Switzerland). The mobile conductivity meter Cond 340i from the company WTW (Weilheim, Germany) was used for the conductivity measurements. The COD was measured by means of the QuickCOD$_{lab}$-03D0318 from the company LAR Process Analysers AG (Berlin, Germany) via a thermal disintegration process. The measurement of TOC and TN was performed with the Analytik Jena TOC analyzer multi N/C 3100 (Jena, Germany). The TS were determined in accordance with DIN 12880, by drying the sample for 6 h, and then, weighing it. TSS were measured in the same way according to DIN 38409-2 only by prior filtration. The ions were measured by means of ion chromatography from Metrohm (Herisau, Schweiz) using a Metrosep A Supp 17–150/4.0 column for anions and a Metrosep C 4–150/4.0 column for cations. The SV was determined using a conical 1 L measuring cylinder.

2.6. PHREEQC Modeling

The PHREEQC software (Version: 3.7.3.15968), developed by the U.S. Geological Survey [21], was utilized to simulate mineral chemistry processes and predict aqueous speciation under various environmental conditions. The input data for the PHREEQC models included ion composition and other measured parameters from the collected water samples. The models were calibrated using experimental data and prior studies on mineral chemistry conducted in similar environments.

2.7. Legal Regulations for the Reuse of Slaughterhouse Wastewater

Regulations play a crucial role in controlling the discharge and reuse of SWW [22]. Various regulations worldwide set limits for emissions, such as the "Urban Wastewater Treatment Directive 91/271/EEC" in the EU and the "Effluent Limitations Guidelines and New Source Performance Standards for the Meat and Poultry Products Point Source" in the USA [23,24]. Limit values for wastewater discharge are referenced from the German Waste Water Ordinance (AbwV) [25] and the "Norme Tunisienne NT 106.002"—Normes Tunisiennes relatives aux rejets d'eaux usées dans les réseaux publics d'assainissement. Targets for potential use of treated wastewater include direct water recycling and water reuse without direct product contact. For assessment purposes, references are made to the "European Drinking Water Regulation" and "EU Regulation on minimum requirements for water reuse" [26,27]. Process water recycling regulations stipulate the drinking water quality according to Directive 98/83/EC [26]. In addition, reuse without product contact places special demands on germ-free conditions due to aerosol formation. Guidelines for evaluating water quality for agricultural irrigation are provided by the European Commission [28], and the Tunisian standard "Environment Protection—Use of reclaimed water for agricultural purposes—Physical, chemical and biological specifications" [29]. Table 1 summarizes the limit values for each category according to existing regulations.

Table 1. Limits for wastewater reuse.

Parameter Reuse Limit	Unit	Process Water Reuse [26] (Drinking Water Quality)	Reuse Without Product Contact [27,30]	Agricultural Irrigation [28,29]	Wastewater Discharge [25,27]
BOD_5	$mg \cdot L^{-1}$	<1	10	10	25
COD	$mg \cdot L^{-1}$	5	-	90	110
Nitrate	$mg \cdot L^{-1}$	50	-	-	-
TOC	$mg \cdot L^{-1}$	No abnormal change	-	-	-
E. coli	$cfu \cdot L^{-1}$	0	0	10	-
Legionella spp.	$cfu \cdot L^{-1}$	-	<1000	1000	-
Turbidity	NTU	10	5	5	-
TSS	$mg \cdot L^{-1}$	-	10	30	35
Conductivity	$\mu S \cdot cm^{-1}$	2500	-	-	-
Na^+	$mg \cdot L^{-1}$	200	-	-	-
NH_4^+	$mg \cdot L^{-1}$	0.5	-	-	-
F^-	$mg \cdot L^{-1}$	1.5	-	-	-
Cl^-	$mg \cdot L^{-1}$	250	-	-	-
NO_3^-	$mg \cdot L^{-1}$	50	-	-	-
SO_4^{2-}	$mg \cdot L^{-1}$	250	-	-	-
pH	-	6.5–9.5	6–9	6.5–8.4	6–9

2.8. Utilization of Artificial Intelligence

AI tools, specifically DeepL (Version: 24.8.2.13437+065a4aef7f5622c450f562a6e3dd06d996cf56f4) and OpenAI's language models, were used to assist with language refinement and grammatical corrections. These tools were applied solely to enhance clarity, readability, and grammatical accuracy, with no changes made to the scientific content of the manuscript.

3. Results and Discussion

Following the installation of all system components, the monitoring phase commenced. The primary objective was to guide the system from its commissioning phase to steady-state operation. Upon successful completion of this period, the system was officially transferred to the slaughterhouse operator. The data collected during this time are analyzed and discussed in the subsequent sections.

3.1. Water Consumption of the Slaughterhouse

The slaughterhouse's fresh water consumption fluctuates with the daily production volume. This is usually between 4000 and 8000 chickens per day, which leads to a water consumption of 45 and 60 m^3, respectively. Table 2 shows how the water consumption for these two cases is divided between the individual production steps. The water consumption per animal decreases significantly with increasing production volumes. Figure 7 visualizes the water consumption of the individual processing steps in the slaughtering process. It is important to distinguish between water that has direct contact with the product and water that is only used to clean the vehicles and the cages, meaning without product contact. This indicates that, depending on the production volume, the potential for reusing wastewater in non-contact applications ranges from 24% to 30%. Lower quality requirements are sufficient for this portion compared to water with product contact. According to the EPA, U.S. Environmental Protection Agency [30], the pH value must be between 6 and 9, the turbidity NTU < 5, the BOD5 < 10 $mg \cdot L^{-1}$, and the water must be germ-free (*E. coli* < 0 cfu in 100 mL).

Table 2. Average daily water consumption in the abattoir based on slaughtering process and number of birds slaughtered.

	4000 Chickens·d^{-1}		8000 Chickens·d^{-1}	
	Water [$m^3 \cdot d^{-1}$]		**Water [$m^3 \cdot d^{-1}$]**	
Killing	2	4.5%	2.2	4%
Scalding	4.5	10%	5	8.5%
Defeathering	14	31.5%	22	37%
Evisceration	6	13.5%	10	17%
Bird wash	4	9%	6	10%
Cleaning	14	31.5%	14	23.5%
Total	44.5	100%	59.2	100%
Demand per bird	11.1 L		7.4 L	

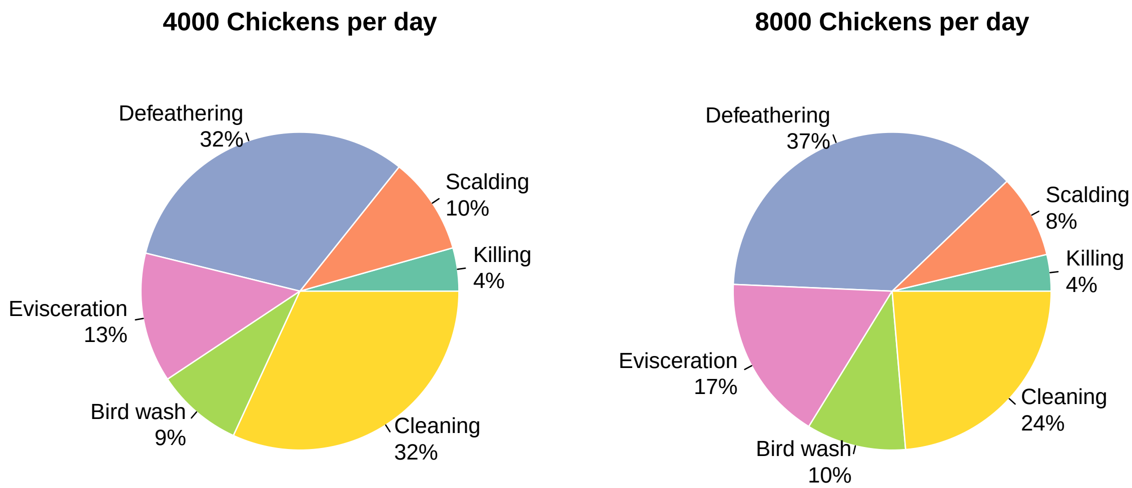

Figure 7. Water demand of the individual processing steps.

3.2. Characteristics of Slaughterhouse Wastewater

Depending on the fluctuating production volume, the site generates between 45 and 65 $m^3 \cdot d^{-1}$ of SWW. The wastewater was analyzed for relevant parameters over the monitoring period and compared with data from the literature. The results are shown in Table 3.

Table 3. Slaughterhouse wastewater characteristics.

Parameter	Unit	SWW Analyzed	BREF [18]	Rosenwinkel et al. [17]
TOC	$mg \cdot L^{-1}$	500–900		
TN	$mg \cdot L^{-1}$	50–150	200–475	150–350
COD	$mg \cdot L^{-1}$	1500–3000	2800–4200	2000–4000
BOD_5	$mg \cdot L^{-1}$		500–2500	1000–2500
TP	$mg \cdot L^{-1}$	5–15		5–30
pH		6.7–7.2	7.0–8.0	

It is noticeable that the measured values are within the expected range for SWW, but the analyzed wastewater shows a rather low level of contamination in comparison. In particular, the nitrogen and phosphorus contamination appears to be at the lower end of the expected values. This can be explained by the fact that the blood is collected separately at the site; this also applies to the wash water from the drainage channel and the blood collection tank.

3.3. Pretreatment

In the first step of the wastewater treatment process, feathers and coarse materials with a diameter larger than 5 mm are extracted using a drum screen. On average, approximately 10 kg_{TS} of coarse material are retained by the drum screen each day. This material is then sent to a rendering plant for further processing. This initial step plays a crucial role in optimizing the efficiency of subsequent processes, particularly the following physical flotation. Without this pretreatment, the pressure relief valve could block, which would prevent the formation of the microbubbles that are essential for the effective transportation of smaller particles to the surface.

Table 4 indicates the performance indicators of the flotation system. As a result, it can be concluded that the reduction rates achieved are below those theoretically possible, especially for the COD [17,31]. This can be explained by the fact that in this case purely physical flotation was used, without the addition of flocculants. At this location, however, the system is able both to comply with the limit values for indirect discharge and to reduce the load on COD and TN to such an extent that the MBR is not overloaded.

Table 4. Performance of the physical flotation unit.

Parameter	Unit	Feed	Outflow	Removal	Theoretical Removal [17,31]
COD	$mg \cdot L^{-1}$	1800	1000	45%	70%
TSS	$mg \cdot L^{-1}$	600	120	75%	80%
TN	$mg \cdot L^{-1}$	130	65	50%	55%

3.4. Membrane Bioreactor

A MBR with a cross-flow membrane was used as the second cleaning stage. The observation period begins with the installation of the new blower and the changeover to 45 min of aeration followed by 15 min of no aeration. Figure 8 shows the oxygen concentration in the aeration tank after the accumulation of sufficient active biomass with the aforementioned aeration cycle. Particularly noticeable is the maximum oxygen concentration at the end of the aeration cycle of 2.5 $mg \cdot L^{-1}$ and the rapid oxygen degradation in the non-aerated phase. Based on the non-aerated phases, the oxygen consumption in the tank can be estimated to be approximately 8 $mgO_2 \cdot L^{-1}h^{-1}$, which is in the normal to high range for activated sludge tanks [32].

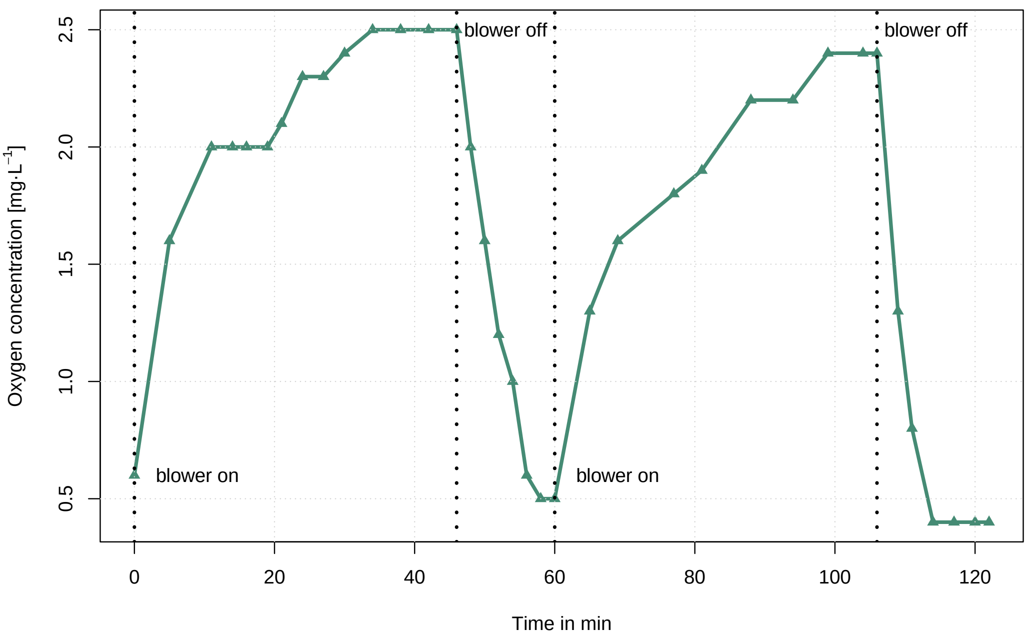

Figure 8. Oxygen concentration in the aeration tank with 45 min aeration followed by 15 min of no aeration.

Figure 9 shows the progression of SV and TSS over the observed period. During intermittent aeration, neither the SV nor the TSS could be sufficiently increased. For this reason, the aeration tank was aerated continuously from day 12 to day 27. The oxygen concentration was kept above 2 $mg \cdot L^{-1}$ throughout the entire period, including at night and at weekends.

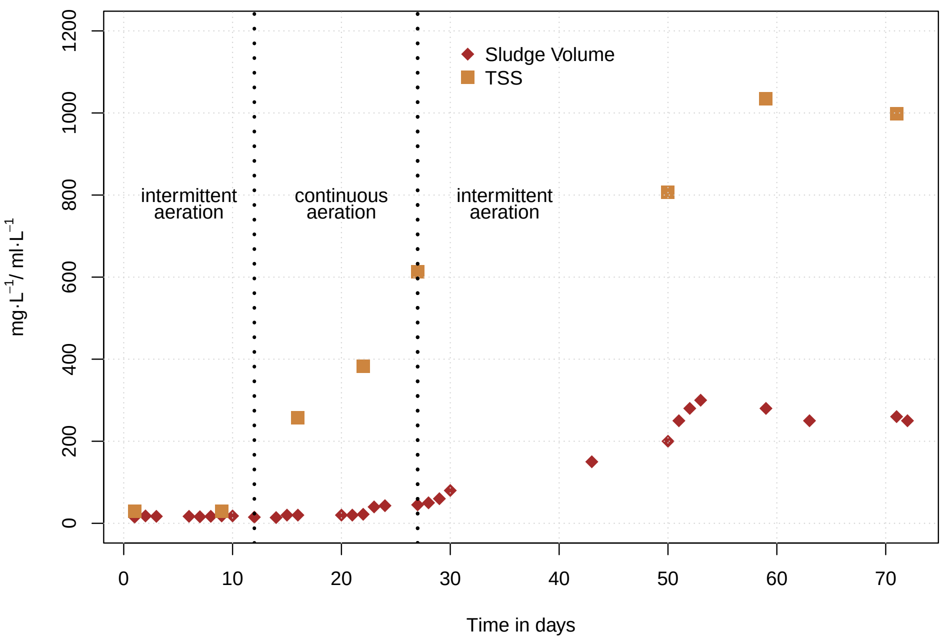

Figure 9. TSS and the sludge volume over the testing period in the aeration tank.

After an increase in TSS was achieved, intermittent aeration was carried out again from day 27 to enable biological removal of nitrogen. From day 30 onwards, the SV increases until it reaches a plateau at 250 mL·L^{-1}. Compared to other aeration tanks, the SV is still relatively low [32].

The TSS remains below 100 mg·L^{-1} until day 10, then rises to 600 mg·L^{-1} with the switch to continuous aeration. In the second phase of intermittent aeration, it continues to increase until reaching a plateau at 1000 mg·L^{-1}. This may be attributed to a temporary overflow of the aeration tank during periods of low transmembrane flux of the UF. However, since the COD load was already sufficiently reduced at these biomass concentrations and the majority of the ammonium could be oxidized, the sludge concentration did not increase further.

Figure 10 shows the course of the ammonium and nitrate concentrations over the same period. At the beginning, most of the nitrogen is present in the form of ammonium, which indicates that there are not enough nitrifying bacteria in the sludge to oxidize the nitrogen. This changes with continued aeration. The ammonium concentration decreases and the nitrate concentration increases. Most of the nitrogen in the tank at the end of this period is in the form of nitrate. This suggests that the nitrifying bacteria could be enriched in the tank. Therefore, intermittent aeration was subsequently carried out to achieve biological nitrogen removal. At the end of the monitoring period, the total nitrogen content in the tank was greatly reduced, which can be attributed to successful biological nitrogen removal.

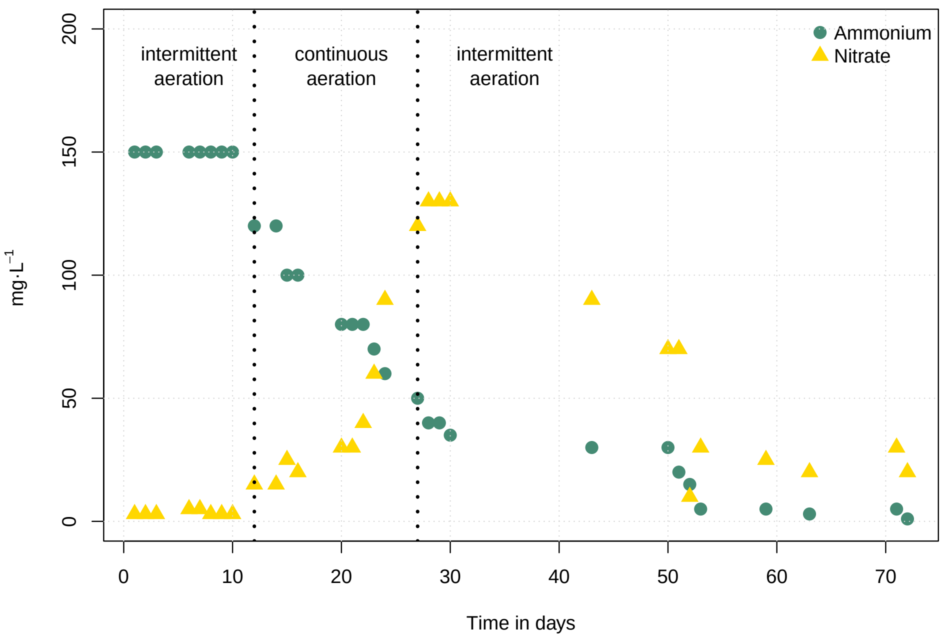

Figure 10. Ammonium and nitrate concentrations in the aeration tank during the testing phase.

Figure 11 shows the flux and the TMP during the observation period. The TMP was adjusted manually when it exceeded 1.5 bar. At the same time, a cross-flow velocity of 4.5 m·s^{-1} was ensured by a circulation pump. On day 21, a drop in the cross-flow velocity occurred due to air bubbles in the system, but this was remedied by degassing. The flux fluctuates between 25 and 50 L·h^{-1}·m^{-2}; after a strong decrease, a "cleaning in place" was carried out with a 1% NaOH solution. For this, 200 L of the solution was circulated in the system until the pH value in the permeate no longer decreased, and the flux was restored to approximately 50 L·h^{-1}·m^{-2}. As the flux was largely restored in this way, it can be assumed that mostly reversible membrane fouling had taken place up to this point. On average, about one chemical cleaning per week had to be carried out to keep the flux stable. This resulted in a chemical consumption of approximately 8 kg of NaOH and 800 L of washing water per month. Towards the end of the monitoring period, the flux dropped to 6 L·h^{-1}·m^{-2}. The membrane modules were therefore dismounted and cleaned. This restored the flux. In the work of Huy Tran et al. [33], a flux of 15 L·h^{-1}·m^{-2} on average was generated in an MBR with sidestream on a laboratory scale using a hollow fiber thin-film membrane with air scouring. In a similar study by Gavlak et al. [34], a flux of 6 L·h^{-1}·m^{-2} could be stably maintained with a submerged hollow-fiber membrane module (Koch membrane systems®) with an outer fiber diameter of 2.6 mm, offering a filtration area of 0.5 m^2 at a TSS concentration of 5 g·L^{-1}. In the work by Hu et al. [35], a flux of 50 L·h^{-1}·m^{-2} was achieved with a cross-flow system on a laboratory scale at a TMP of 0.6 bar at TSS concentrations of up to 6 g·L^{-1} using different membranes (0.1 µm polyacrylonitrile (PAN), 0.1 µm polyethersulfone (PES), and 0.1 µm polyvinylidene fluoride (PVDF) microfiltration flat sheet). A higher flux was achieved in the work of Issa [36], where a peak value of 195 L·h^{-1}·m^{-2} was achieved by using small sponge balls for membrane cleaning in a 1″ UF cross-flow membrane module with a cross-flow velocity of 4 m·s^{-1}. As a result, the system investigated here is in the lower middle range for MBR applications with cross-flow filtration.

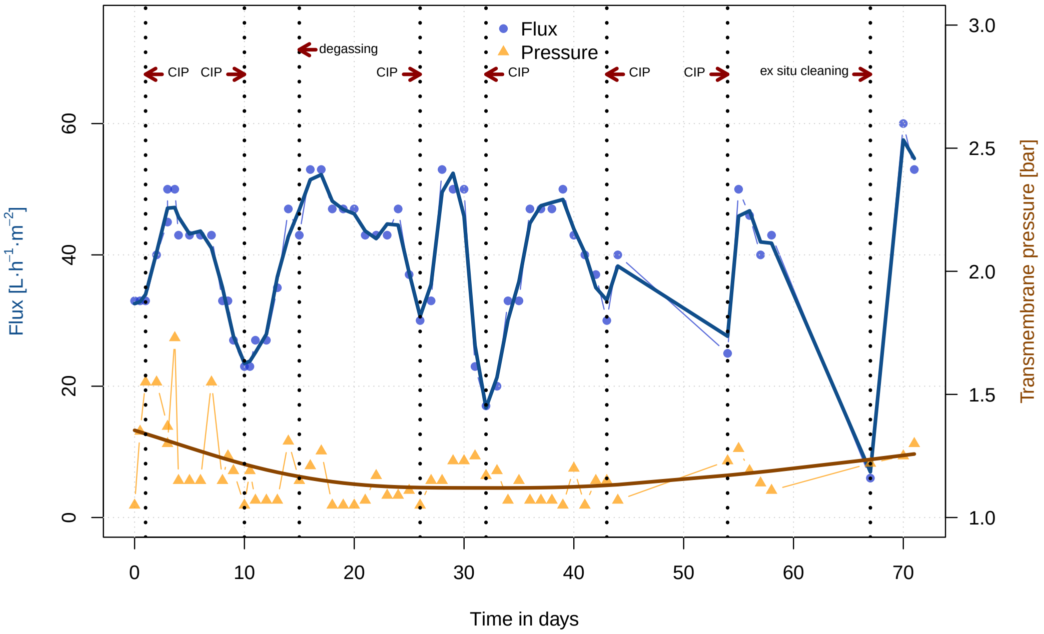

Figure 11. Flux and transmembrane pressure of the ultrafiltration membrane during the testing period with "cleaning-in-place" (CIP) chemical cleanings with NaOH recorded.

Table 5 shows the performance of the MBR at the end of the monitoring period. A reduction in COD of over 90% to 80 mg·L^{-1} and in TN of 80% to 10 mg·L^{-1} was achieved. The highest TSS concentration in the reactor was 1 g·L^{-1}, which corresponds to an average sludge load of 0.9 kgCOD·kgTS^{-1}·d^{-1}. In the work of Lau et al. [37], the COD could be reduced to 15 mg·L^{-1} and the ammonium nitrogen to 0.1 mg·L^{-1}, but a two-stage biological purification system was used here.

Keskes et al. [7] investigated the performance of an MBR for the treatment of SWW with an initial average COD concentration of 2000 mg·L^{-1}. A high removal efficiency of 98% was achieved. The COD concentration decreased to 25 mg·L^{-1}. The reactor was operated at a sludge load of 0.8 kgCOD·kgTS^{-1}·d^{-1} at an average TSS concentration of 3 g·L^{-1}. This means that the COD and TN reductions were lower compared to other studies [7,17,37]. This could be due to the fact that the biomass concentration in the reactor was low until the end of the monitoring period and the recommended sludge load of 0.12 kgCOD·kgTS^{-1}·d^{-1} [17] was exceeded.

In comparison with the limit values for agricultural irrigation in Tunisia, the local requirements for water quality can be met. In comparison with the limit values applicable in the EU, it should still be verified whether the microbial parameters are complied with and whether the limit value for nitrate of 50 mg·L^{-1} can be maintained permanently [38].

Table 5. Performance of the membrane bioreactor and comparison with the Tunisian limits for agricultural irrigation.

Parameter	Unit	Feed	Outflow	Removal	Theoretical Outflow [7,17,37]	Theoretical Removal [7,17,37]	Irrigation Limit [29,39]
COD	$mg \cdot L^{-1}$	1000	80	92%	25	95%	90
TOC	$mg \cdot L^{-1}$	280	5	98%	-	-	-
TN	$mg \cdot L^{-1}$	65	10	80%	8	85%	-
TP	$mg \cdot L^{-1}$	15	5	65%	4	70%	-

3.5. Reverse Osmosis

After the biological process has treated the SWW to irrigation-water quality, the RO system should treat the water to process-water quality. The transmembrane flux is a key performance indicator for RO systems. Figure 12 shows the flux and the permeability of the RO during the monitoring period. The flow decreases sharply in the first 20 days and drops to 5 $L \cdot h^{-1} \cdot m^{-2}$. The transmembrane flux could be restored by cleaning with 1% NaOH solution and subsequent acid cleaning with citric acid solution at pH 3, but the flux drops sharply again. Chemical cleaning was carried out regularly to restore the flux. From day 50, the flux appears to be more stable. This is because, from that point onward, the MBR was optimized, resulting in improved effluent quality. However, the flux continues to decrease over time and can only be regenerated by acid cleaning. This leads to the conclusion that at the beginning, biological fouling strongly reduced the flux, which could be improved by a better MBR performance. At the end of the monitoring period, mineral scaling seems to predominate. As this can be negated by acid rinsing, it is reasonable to assume that these are acid-soluble compounds. During the monitoring period, the chemicals required to clean the RO system were 6 kg of citric acid, 2 kg of NaOH and around 600 L of washing water per month. In the work by Coskun et al. [8], a flux of 30 $L \cdot h^{-1} \cdot m^{-2}$ was achieved at a TMP of 20 bar. In a comparable study by Brião et al. [40], a flux of 20 $L \cdot h^{-1} \cdot m^{-2}$ was achieved at a TMP of 20 bar. Compared to this work, a lower flux was achieved here. On the one hand, this can be attributed to the maximum TMP of 13 bar, which was due to the system, on the other hand, it can be assumed that scaling effects took place on the membrane surface [8,40].

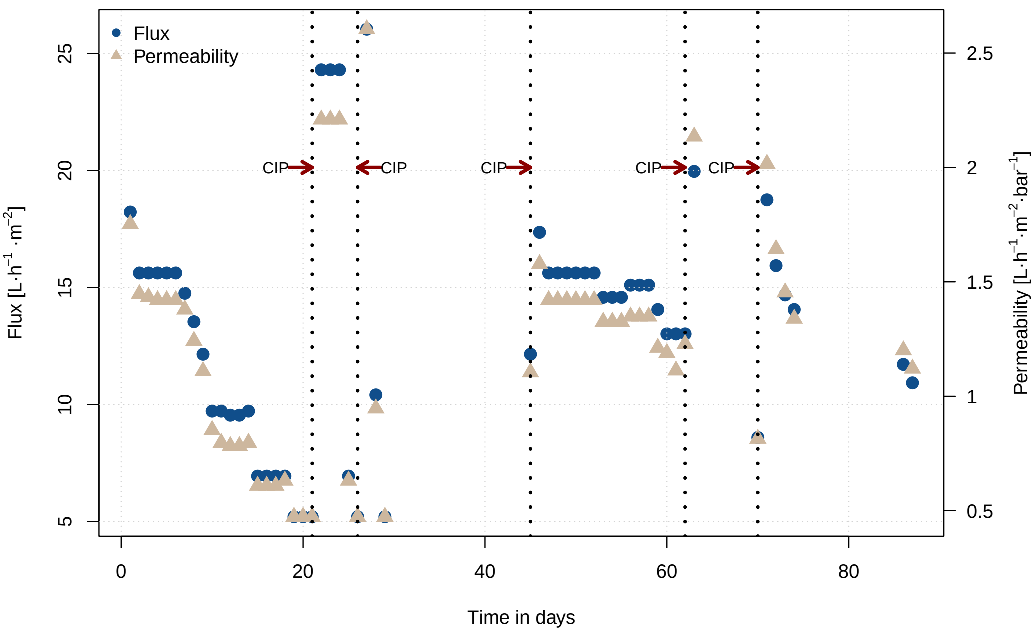

Figure 12. Flux and permeability of the reverse osmosis membrane during the testing period with "cleaning-in-place" (CIP) chemical cleanings with citric acid and NaOH recorded.

In order to take a closer look at the possible mineral scaling, the saturation index of potential minerals was calculated using the PHREEQC software on the basis of the measured ion composition in the concentrate. Table 6 lists the saturation index of the minerals likely to be present in the solution. The saturation index indicates the degree of saturation of a mineral in water, with positive values suggesting supersaturation (and potential for precipitation) and negative values indicating undersaturation, where dissolution is more likely. The saturation index is only positive for hydroxyapatites, but the saturation index for calcines, aragonites, and gypsum is already higher than −1. All of these minerals are calcium composites, which are typical for the region. It is therefore reasonable to assume that the reduction in flux is due to mineral precipitation on the membrane surface. The mineral species also explain why the flux could be restored by acidic cleaning. For long-term operation of the system, the use of anti-scaling agents or prior removal of calcium should be considered.

Table 6. Saturation index of minerals in the reverse osmosis concentrate.

Mineral	Chemical Formula	Saturation Index
Hydroxyapatite	$Ca_5(PO_4)_3OH$	5.51
Calcite	$CaCO_3$	−0.45
Aragonite	$CaCO_3$	−0.60
Gypsum	$CaSO_4 \cdot 2H_2O$	−0.77
Anhydrite	$CaSO_4$	−1.08
Dolomite	$CaMg(CO_3)_2$	−1.32
Sylvite	KCl	−6.17

Table 7 shows the performance of the RO system at the end of the monitoring period and compares it with the limit values for drinking water. Most parameters can be reduced by more than 90%, except COD and TN, where a reduction of more than 80% was achieved. The manufacturer specifies a retention rate of 85–99% for COD, approximately 90% for nitrate, and 70–80% for ammonium, depending on the wastewater characteristics [41]. These values were confirmed here. It is apparent that in this system it is advantageous to operate with more nitrate than ammonium in the effluent of the MBR. In comparison with previous works, a comparable retention of 90% for COD could also be observed by Coskun et al. [8], whereas in the case of Bohdziewicz and Sroka [42] the retention was lower, at 85%. In the work of Brião et al. [40], a retention of TN of over 99% was achieved, but the nitrogen species was not determined in more detail in this work. The RO permeate complies with the limit values for drinking water, which means that it can be used as process water. At the demonstration site, the water was used for cleaning tasks without product contact. Ultimately, wastewater recycling in the food industry is not only a technical challenge but also a legal one and a question of social acceptance of such an approach.

Table 7. Reverse osmosis performance and comparison with the limit values for process water recycling of the European Union.

Parameter	Unit	UF—Permeate	RO—Permeate	RO—Concentrate	Removal [%]	Reuse Limit [26]
pH	-	7	7	7	-	6.5–9.5
Turbidity	NTU	0.83	0.12	1.1	-	1
Conductivity	$\mu S \cdot cm^{-1}$	2000	80	3800	95	2500
COD	$mg \cdot L^{-1}$	35	4	80	89	5
TOC	$mg \cdot L^{-1}$	<5	1	4	-	n.a.c.*
TN	$mg \cdot L^{-1}$	10	2	45	80	-

Table 7. *Cont.*

Parameter	Unit	UF—Permeate	RO—Permeate	RO—Concentrate	Removal [%]	Reuse Limit [26]
K^+	$mg{\cdot}L^{-1}$	27	2	50	93	-
Ca^{2+}	$mg{\cdot}L^{-1}$	105	<0.01	193	>99	-
Mg^{2+}	$mg{\cdot}L^{-1}$	15	<0.01	36	>99	-
Cl^-	$mg{\cdot}L^{-1}$	97	2	203	98	250
NH_4-N	$mg{\cdot}L^{-1}$	2	<0.01	4	>98	0.5
$NO_3{}^-$	$mg{\cdot}L^{-1}$	5	<0.01	10	>99	50
$SO_4{}^{2-}$	$mg{\cdot}L^{-1}$	217	<0.01	430	>99	250
$PO_4{}^{3-}$	$mg{\cdot}L^{-1}$	20	<0.01	30	>99	3

* no abnormal changes.

3.6. Evaluation of the Combined System

After examining the individual process steps, the overall system is evaluated. Figure 13 shows a Sankey diagram of the entire process. The COD, TN, TS, and electrical conductivity were selected as representative key parameters for the evaluation. Most of the organic impurities are removed in the first two process steps. The inorganic impurities, on the other hand, are separated by reverse osmosis. It is noticeable that the amount of sludge to be disposed of is low. This is due to the fact that the maximum sludge concentration in the aeration tanks had not yet been reached at the end of the monitoring phase, and therefore, no excess sludge had to be removed. Theoretically, the excess sludge production should be 32 $kgTS{\cdot}d^{-1}$. How the biological system behaves over a longer period of time therefore remains the subject of observation. With the installed system, around 35% of the wastewater produced daily can be treated to drinking-water quality. A third can be used for irrigation, and the rest is still discharged indirectly. This means that fresh water consumption at the site can be reduced by around 35% and wastewater discharge reduced by around 70%. As a result, the original targets for the plant have been achieved.

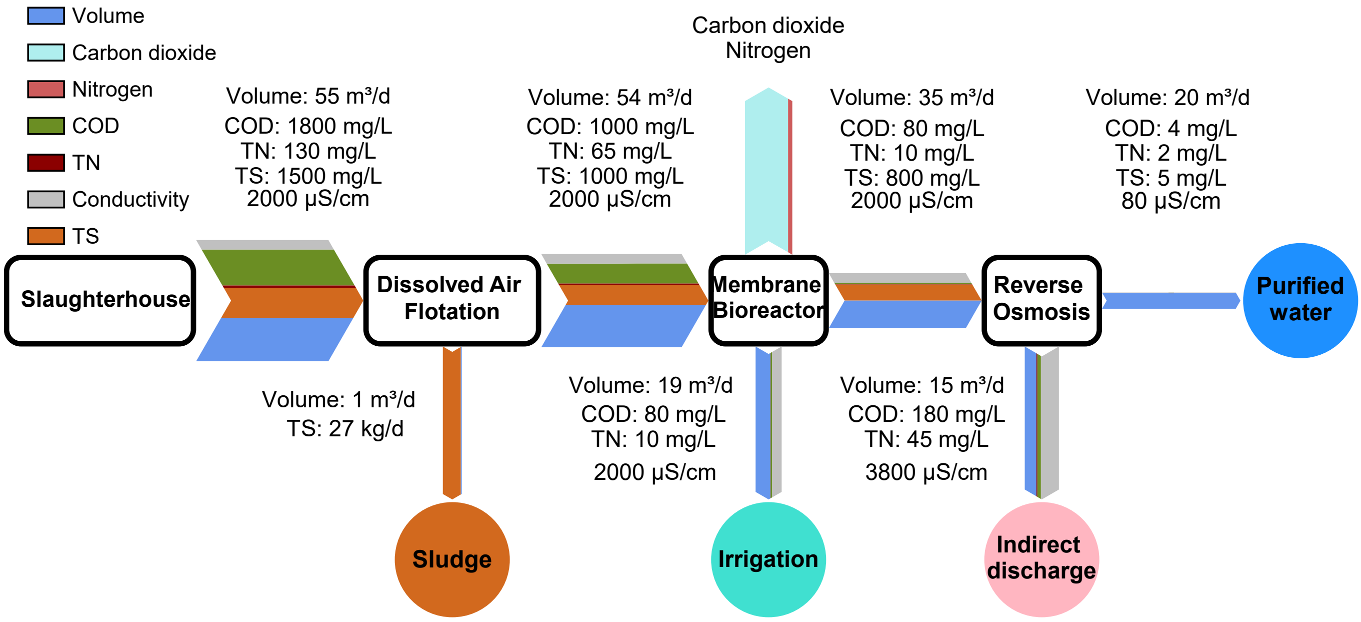

Figure 13. Balance of the full-scale wastewater recycling system based on the results.

3.7. Energy Consumption of the System

In addition to the technical performance, the energy consumption should also be considered when evaluating the system. Table 8 shows the average energy consumption of the individual process steps in comparison with energy consumption data from other studies. In order to record the energy consumption of each treatment process, the daily operating times for the individual consumers were recorded and offset against their power consumption.

Table 8. Energy consumption of each treatment process.

Process	Electrical Energy Consumption [$kWh \cdot m^{-3}$]	Theoretical Energy Consumption [$kWh \cdot m^{-3}$]
Flotation	0.3	0.03–0.3 [43,44]
Membrane bioreactor	3.8	0.4–4 [45–48]
Reverse osmosis	1.1	0.5–0.8 [49,50]

A comparison with other systems shows that the specific energy consumption is high. The flotation is at the upper end of the typical energy consumption for this technology, although it is still the technology with the lowest specific energy consumption of the entire process.

The MBR is also at the upper end of the specific energy consumption in comparison. This is due to the fact that it is a pilot plant that was not designed to minimize energy consumption. The plant did not have the necessary monitoring and control equipment to minimize energy consumption. Neither the pumps nor the blower could be regulated in their output. The volume flows were only regulated by closing and opening valves, which led to a considerable loss of energy. Also, only a comparatively small amount of wastewater of about 55 $m^3 \cdot d^{-1}$ is treated here; the comparison of many plants has shown that the specific energy consumption decreases with increasing wastewater volume [48]. A reduction in specific energy consumption therefore appears realistic with optimized design and at larger sites.

The relatively high specific energy consumption observed with the RO system can be attributed to the fact that the high-pressure pump was not controlled via a frequency converter. Instead, the feed to the modules was regulated using a valve, which needed to be 70% closed during normal operation to maintain a system pressure of 13 bar. As a result, the system required 4.1 kWh to produce 1 m^3 of irrigation water and 5.2 kWh for 1 m^3 of process water.

4. Conclusions

The recycling of SWW was demonstrated. At the end of the monitoring phase, steady-state operation was achieved, demonstrating the feasibility of transferring research results into practical applications. The system is capable of treating wastewater up to two quality levels, including drinking-water quality. In the process, 35% of the wastewater produced could be treated up to the standard for agricultural irrigation. A further 35% of the total wastewater could be purified to process-water quality, resulting in a significant reduction of 70% in wastewater discharge at the site. The energy consumption of the plant is high. However, even under non-optimal conditions, 4.1 kWh was required to produce 1 m^3 of irrigation water, and 5.2 kWh for 1 m^3 of process water. In the framework of this project, a wastewater recycling system was developed. The next step would involve scaling up the system. However, the legal feasibility of reusing slaughterhouse wastewater in different countries and its social acceptance remain open questions.

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Abbreviations

COD	Chemical oxygen demand
MBR	Membrane bioreactor
RO	Reverse osmosis
SV	Sludge volume
SWW	Slaughterhouse wastewater
TMP	Transmembrane pressure
TN	Total nitrogen
TOC	Total organic carbon
TS	Total solids
TSS	Total suspended solids
UF	Ultrafiltration

Appendix A. Wastewater Treatment Plant before Implementation of the Wastewater Recycling System

Figure A1. Wastewater treatment plant before implementation of the wastewater recycling system: (1) Pump basin before screening; (2) flotation; (3) drum screen; (4) sedimentation tank; (5) second drum sieve; (T1) first aeration tank, later used as a mixing and equalization tank; (T2) second aeration tank; (T3) buffer tank, later used as ultrafiltration permeate storage; (T4) third aeration tank, later used as a reverse osmosis permeate storage tank.

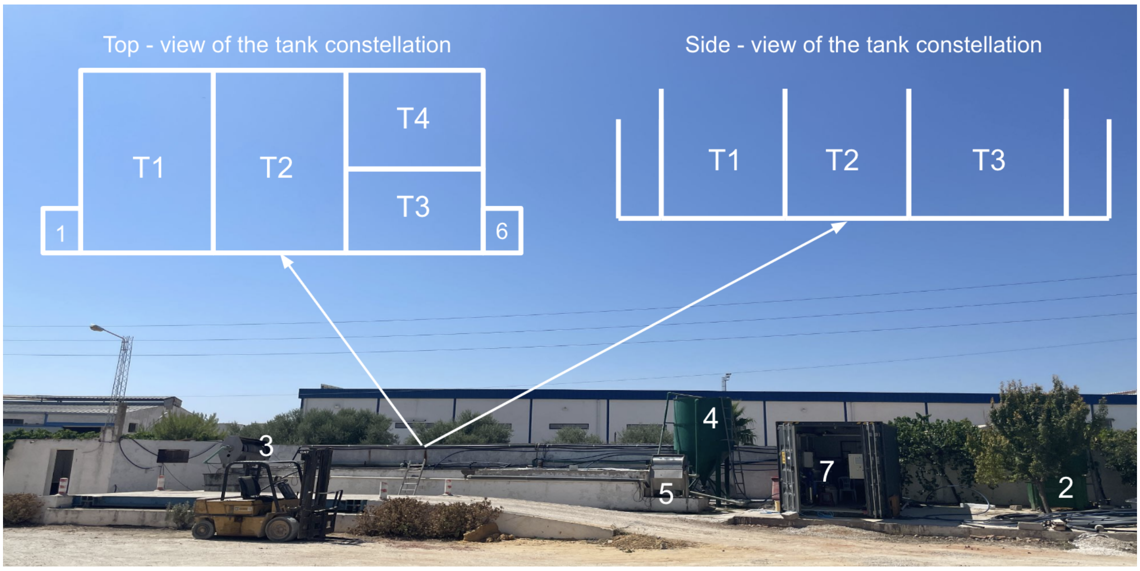

Figure A2. Basin overview after modification: (1) Pump basin before screening; (2) flotation; (3) drum screen; (4) sedimentation tank; (5) second drum sieve; (6) pump basin after second screening; (7) containerized waste water recycling plant; (T1) first aeration tank, later used as a mixing and equalization tank; (T2) second aeration tank; (T3) buffer tank, later used as ultrafiltration permeate storage; (T4) third aeration tank, later used as a reverse osmosis permeate storage tank.

Appendix B. Process Flowsheet

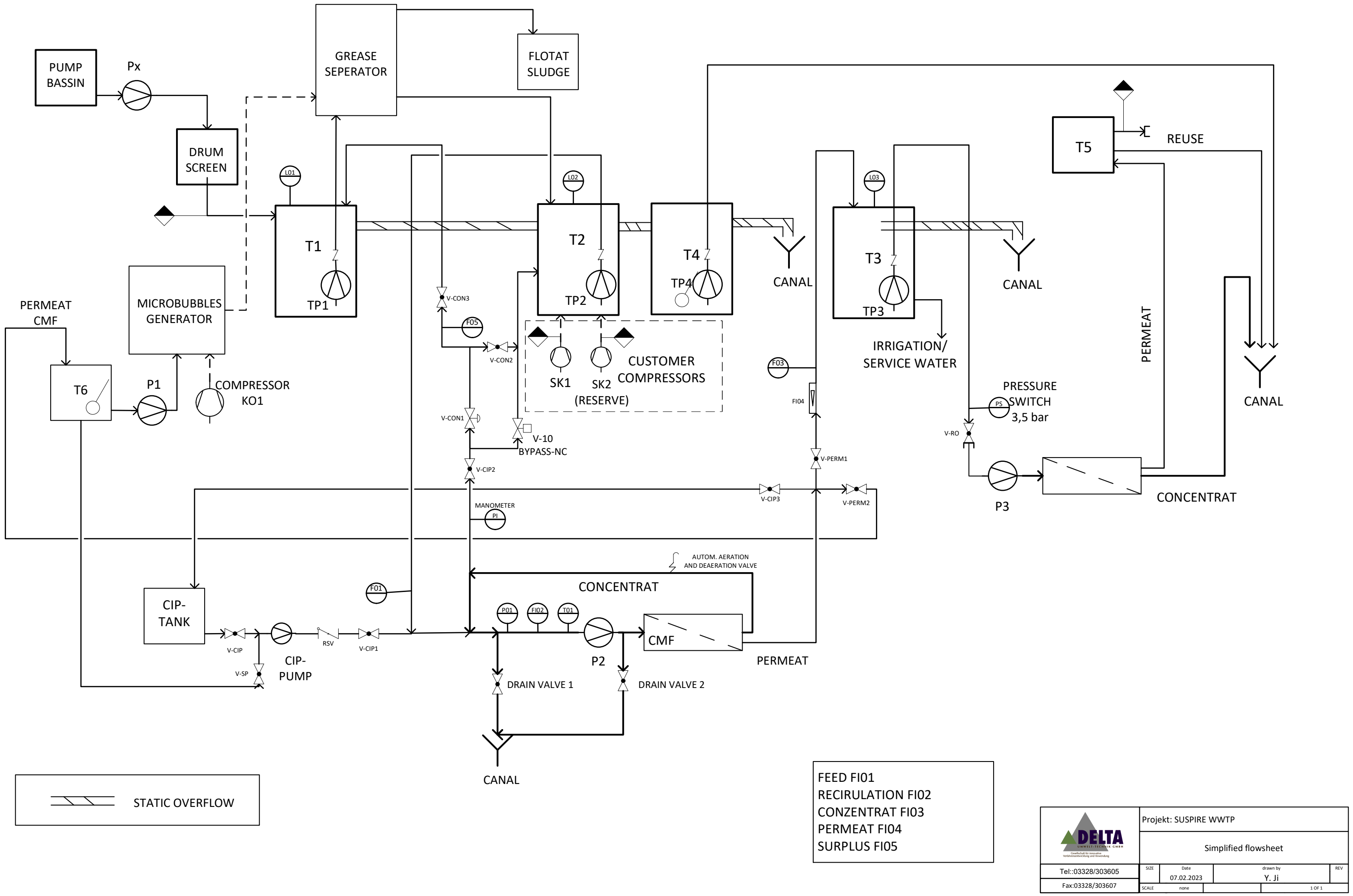

Figure A3. Extended process flowsheet.

Appendix C. Container System

Figure A4. Containerized system with ultrafiltration (1), white water generator (2), and reverse osmosis (3).

Appendix D. Rudolf Messner Umwelttechnik AG: Aerator Plates

Figure A5. Rudolf Messner Umwelttechnik AG: aerator plates.

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