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Abstract: Using wastewater in response to water-related challenges from climate variation has gained significance. Various sophisticated technologies have been developed to meet the demand for wastewater treatment and reuse. Graywater, an intrinsic component of wastewater, is acknowledged for its practical potential in the context of reuse. Decentralized wastewater treatment systems, exemplified by Moving Bed Biofilm Reactors (MBBRs), have emerged as efficient alternatives in urban settings. By comparing the physicochemical analyses conducted in the three treatment units and evaluating the treatment efficiency of each unit, we will first establish the validity of the MBBR system for treating and recycling graywater, achieving up to 98% elimination rates for BOD5. Subsequently, the possibility of optimizing the system will be explored by evaluating the different treatment stages of MBBR reactors.

Keywords: urban graywater; wastewater reuse; decentralized treatment; MBBR system efficacy

1. Introduction

Water scarcity is a multifaceted challenge with profound implications for global sustainability, requiring innovative approaches to water resource management [1]. In this context, wastewater reuse emerges as a promising strategy for alleviating water stress by effectively recycling and reallocating water resources that would otherwise be discarded [2]. By harnessing graywater and implementing decentralized wastewater treatment systems, societies can effectively conserve and recycle water resources [3], thereby mitigating the impacts of water scarcity on communities, ecosystems, and economies [4].

Wastewater, traditionally considered a burden and a health hazard, contains valuable nutrients, organic matter, and water that can be recovered and reused through appropriate treatment processes [5]. Graywater, i.e., wastewater generated by domestic activities such as bathing, laundry, and dishwashing, represents a significant proportion of domestic wastewater [6,7]. Despite its relatively low level of contamination compared to sewage, graywater can be recovered and put to good use [8].

Scientific research underlines the potential of graywater reuse to increase water reserves sustainably [9]. Studies have demonstrated the feasibility and effectiveness of treating and reusing graywater for various non-potable applications, including landscape irrigation, wash machines, toilet flushing, and urban agriculture [10,11]. Graywater will mainly recycle water and supply only minor amounts of nutrients that can contribute to sustainable agricultural practices and food security [12,13].

In addition to graywater reuse, decentralized wastewater treatment systems have attracted attention as decentralized approaches to wastewater management [14]. These systems, which treat wastewater at or near the point of production, offer several advantages over conventional centralized treatment plants [15]. By minimizing the need for extensive...
infrastructure and reducing the energy consumption associated with long-distance transport, decentralized systems improve resource efficiency and resilience in water scarcity and climate variability [16,17].

Scientific literature provides ample evidence of the effectiveness and benefits of wastewater reuse and decentralized wastewater treatment [18]. Researchers have elucidated these approaches’ technical, economic, and environmental dimensions through rigorous experimentation, modeling, and analysis, informing policy and decision-making processes at local, regional, and global scales [19].

The results of a study [20] comparing different graywater treatment technologies concluded that biological treatment is highly efficient for graywater recovery—Table 1 summarizes the technologies compared. However, good discharge values can be achieved with different chemical and physical treatment processes. It is a question of dimensioning. Other factors, such as costs, maintenance requirements, longevity, etc., should be considered.

### Table 1. Technologies for graywater treatment [20].

<table>
<thead>
<tr>
<th>Graywater Treatment System</th>
<th>Graywater Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parameter</td>
</tr>
<tr>
<td>Aerobic MBR (pilot-scale)</td>
<td>CODt</td>
</tr>
<tr>
<td></td>
<td>BOD$_5$</td>
</tr>
<tr>
<td></td>
<td>Ammonia</td>
</tr>
<tr>
<td></td>
<td>Nitrate</td>
</tr>
<tr>
<td>Aerobic membrane sequencing batch reactor (pilot-scale)</td>
<td>CODt</td>
</tr>
<tr>
<td></td>
<td>BOD$_5$</td>
</tr>
<tr>
<td></td>
<td>Ammonia</td>
</tr>
<tr>
<td></td>
<td>Nitrate</td>
</tr>
<tr>
<td>SBR + Ultrafiltration (pilot-scale)</td>
<td>CODt</td>
</tr>
<tr>
<td></td>
<td>BOD$_5$</td>
</tr>
<tr>
<td></td>
<td>Ammonia</td>
</tr>
<tr>
<td></td>
<td>Nitrate</td>
</tr>
<tr>
<td>Aerobic MBBR (pilot-scale)</td>
<td>CODt</td>
</tr>
<tr>
<td></td>
<td>TN</td>
</tr>
<tr>
<td></td>
<td>Total P</td>
</tr>
<tr>
<td></td>
<td>BOD$_5$</td>
</tr>
</tbody>
</table>

Note(s): MBR: membrane bio-reactor; SBR: Sequencing batch reactor; MBBR: moving bed biofilm reactor; NR: not reported; TN: total nitrate; Total P: total phosphate.

Moving Bed Biofilm Reactor (MBBR) systems for graywater treatment and reuse represent a scientifically grounded approach to addressing water scarcity challenges while promoting sustainable water management practices [21]. Studies have shown that MBBR systems can achieve high removal efficiencies for suspended solids, biochemical oxygen demand (BOD), total nitrogen, and total phosphorus, producing treated effluent that meets regulatory requirements for reuse in irrigation, toilet flushing, and industrial processes [22,23].

Despite the extensive research on the Moving Bed Biofilm Reactor (MBBR) system, as shown in Table 1, there is a notable gap in studies evaluating its effectiveness on a practical scale. The majority of existing research has been confined to laboratory settings. Therefore, it is crucial to investigate and report on the performance and effectiveness of the MBBR system in actual laboratory conditions and practical applications.

In this study, we explore the application of Moving Bed Biofilm Reactor (MBBR) systems for treating and reusing graywater in practical settings in Berlin. This investigation
focuses on assessing the effectiveness of MBBR systems in reducing various physicochemical parameters, such as biological oxygen demand (BOD), chemical oxygen demand (CODt), conductivity, orthophosphate, and nitrate, among others. Our analysis goes beyond conventional influent and effluent evaluations, extending to the movement of constituents through different reactor units. This comprehensive approach allows us to understand the specific contributions of each treatment stage to overall contaminant removal efficiency for MBBR for graywater treatment and reuse for urban sustainability.

2. Materials and Methods

2.1. Description of the Study Area

The investigation was conducted at three Moving Bed Biofilm Reactor (MBBR) treatment facilities situated within Berlin, each located in distinct residential complexes or multi-family dwellings that accounted for 86.6% of all Berlin dwellings [24], and receiving graywater of varying categories at their respective inlets. This research was conducted in collaboration with Nolde-Innovative Wasserkonzepte GmbH, Berlin, Germany. Specifically, the first treatment plant is in Pilot 1, the second in Pilot 2, and the third within Pilot 3 of the Roof Water Farm. A visual depiction of the 3 case studies’ location in Berlin of these facilities is provided in the subsequent Figure 1. The dark blue color indicates the locations of the treatment plants within the building. In pilots 1 and 2, the treatment systems are situated in the basement, while in pilot 3, the plant is located outside, in the garden behind the building.

![Figure 1. The case study locations in Berlin.](image)

2.2. General Description of the MBBR Treatment Plant in Case Studies

The MBBR system consists of a bioreactor tank filled with bio-carriers that provide a large surface area for biofilm growth. Microorganisms on the carriers degrade organic pollutants. The system includes an aeration mechanism for oxygen supply and mixing to ensure an even distribution of carriers. The 3 pilot plants use identical systems:
The suspended bio-carriers utilized within the treatment process consist of polyether (PU)-based polyurethane foams characterized by an open-pore structure (EMW, filter technique). These bio-carriers exhibit a net density ranging between 20 and 30 kg/m$^3$, with a pore count of 40 to 50 pores per inch (PPI), and a specific surface area of approximately 1000 m$^2$ m$^{-3}$ [25,26]. The packing density of the foam cubes amounts to roughly 20%. Aeration is facilitated by two air blowers dedicated to each bioreactor. Following tertiary treatment via sand filter and UV irradiation, the treated effluent is stored within a reservoir and subsequently pumped for use in toilet flushing purposes and washing machines [27].

The three treatment systems utilize the same processes and principles but differ in the number of reactors, treatment stages, and reactor capacity and volume based on the specific needs of each building. It is also important to note that 3 graywater treatment pilots receive completely different graywater inlet sources and completely different daily flow rates. The following sections describe these differences for each pilot plant.

2.2.1. Description of the Treatment Plant in Pilot 1

The wastewater treatment facility is situated within the underground level of a residential structure, accommodating 14 apartments with an average occupancy of 45 individuals. Graywater originating from showers and baths is conveyed via gravitational means to a storage reservoir located within the basement of the building for subsequent treatment. Here, the treated graywater is recycled for toilet flushing and washing machines.

The treatment process encompasses biological treatment employing one Moving Bed Biofilm Reactor (MBBR) unit, each possessing a daily treatment capacity of 950 L, supplemented by a UV disinfection stage (Figure 2).

Figure 2. Graywater MBBR system in Pilot 1.

2.2.2. Description of the Treatment Plant in Pilot 2

The graywater treatment facility is in a newly constructed residential building in Pankow, Berlin, as shown in Figure 1. It surpasses its counterpart on Pilot 1 in scale, as it...
skillfully manages wastewater from showers, hand washing, and laundry facilities in a structure accommodating 39 residential units and around 120 residents.

The treatment infrastructure includes a Moving Bed Biofilm Reactor (MBBR) configuration, comprising 5 reactors subdivided into three sequential treatment phases, with a defined daily treatment capacity of 4 m$^3$. Initial graywater entry is via a dedicated chamber outside the main plant, which is then pumped into the treatment plant in a monitored system, as shown in Figure 3.

The plant includes a heat exchange mechanism designed to harness the thermal energy of the incoming water flow. After treatment, the reclaimed water is evaluated for potential application in the same building’s toilet flushes and washing machines and for future use for irrigation in urban agriculture initiatives.

2.2.3. Description of the Treatment Plant in Pilot 3

The “Block 6” model project, or Pilot 3, situated within Berlin’s Friedrichshain-Kreuzberg district in Germany, incorporates an integrated water management approach originally developed during the 1987 International Building Exhibition (IBA) [28]. The study area, Pilot 3, encompasses centrally located community housing comprising three residential buildings housing 71 families (approximately 223 tenants), all linked to a graywater recycling system [25].

It is pertinent to highlight that the Moving Bed Biofilm Reactor (MBBR) under investigation is a newly implemented system having undergone renewal in 2023. Graywater sourced from showers, baths, washbasins, kitchen activities, and laundry facilities is reclaimed and repurposed for toilet flushing, facilitated by these updated MBB reactors and sedimentation tanks [26], followed by an MBBR tank after the sedimentation tank. Figure 4 schematizes the treatment and graywater flow path in the different stages of treatment.
2.3. Sampling

All samples collected to analyze physicochemical parameters were obtained by established sampling protocols conforming to DIN standards. The sampling procedure was designed to be proportional to the quantity of the graywater inlet. These samples were promptly refrigerated at 4 °C (Figure 5) and processed within a 24-h timeframe to minimize potential alterations in their physicochemical characteristics [29]. Primarily, 24-h composite samples were collected to ensure representative sampling (Figures 6 and 7), adhering to the sampling procedures adhered to the established norms and guidelines outlined in DIN 38402-11 (2009) and ISO 5667-1:2019-09 [30], providing standardized water analysis protocols and sampling techniques. It is noteworthy that, apart from sampling treated wastewater and drinking water (as a reference to compare the treated water quality in Pilot 2), the sampling campaign spanned two weeks (10 days) for each treatment plant. The sampling regimen was consistently applied across different periods to ensure consistency and reliability of the data obtained (Table 2).
The subsequent table provides a comprehensive summary detailing the sampling points and corresponding methodologies employed for each sampling point by DIN 38402-11 and ISO 5667-1:2019-09. Sample collection was conducted uniformly across all three stations. At each designated sampling location, as delineated in Figures 2–4 enumerated in Table 1 to denote a 24-h sampling interval (Figure 7), a tube was affixed to a Dosita pump (depicted in Figure 6) affixed to the reactor cover. The pump, synchronized with the primary system pump via an electrical signal, facilitated the extraction of a sample proportionate to the volume pumped. Subsequently, these samples were amassed within a 5-L sampling vessel stored within a refrigerated environment.

Table 2. Sampling points and sampling periods.

<table>
<thead>
<tr>
<th>Pilot</th>
<th>Storage tank</th>
<th>MBBR2</th>
<th>MBBR3</th>
<th>MBBR5</th>
<th>Treated water storage tank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot 2</td>
<td>After the sieve (pipe)</td>
<td>02.02.23—17.02.23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot 1</td>
<td>Graywater tank</td>
<td>MBBR2</td>
<td>Treated water tank</td>
<td>06.06.23—15.06.23</td>
<td></td>
</tr>
<tr>
<td>Pilot 3</td>
<td>Sieve 2</td>
<td>MBBR 2</td>
<td>MBBR 8</td>
<td>After sedimentation tank</td>
<td>01.11.23—14.11.23</td>
</tr>
</tbody>
</table>

Sampling method

- 24-h systematic sampling volume proportional
- Random sampling
pump (depicted in Figure 6) affixed to the reactor cover. The pump, synchronized with the primary system pump via an electrical signal, facilitated the extraction of a sample proportionate to the volume pumped. Subsequently, these samples were amassed within a 5-L sampling vessel stored within a refrigerated environment.

2.4. Analytical Procedures

The samples were collected and transported to the physicochemical analysis facility in the Department of Urban Water Management at Berlin Technical University. Laboratory evaluations were carried out within 12 h of sample acquisition (Figure 8). In situ parameters, such as pH, temperature, and dissolved oxygen, were measured at each sampling site using a Hach multi-parameter instrument (HQ40d Portable) from Hach Lange GmbH, Düsseldorf, Germany.

Figure 8. Physicochemical analysis for the samples of the graywater from the system in Pilot 3.

Graywater measurements evaluated the physical and chemical composition of the samples from the 3 case studies and proceeded in the same way. Parameters such as total chemical oxygen demand (CODt) and soluble COD (CODs), orthophosphate \( \text{PO}_4^{3-} \), nitrate \( \text{NO}_3^- \), nitrite \( \text{NO}_2^- \), ammonium \( \text{NH}_4^+ \), and ammonium \( \text{NH}_4^- \) were analyzed using cuvette tests from the Hach Lange DR6000. The biological oxygen demand (BOD5) measurement was performed using the respirometric method with OxiTop systems of WTW. Turbidity was measured using Hach 2100Q analyzers and given in FNU units (FNU is most often used for referencing the ISO 7027 (European) turbidity method). All parameters were double-measured, respecting the German standard procedures [31].

3. Results and Discussion

3.1. Treatment Plant in Pilot 1

To clarify the requirements for reuse, Table 3 sets out the quality standards for the reuse of graywater and wastewater for domestic and irrigation purposes. The results obtained from the analysis that presents physicochemical parameters in the treatment plant at Pilot 1 are presented in Table 4. These results provide crucial insights into the treatment system’s efficacy in organic compound removal and water quality improvement.

Firstly, the average concentrations of chemical oxygen demand (CODt) and biochemical oxygen demand (BOD5) in the graywater samples were observed to be 122.4 mg/L and 69 mg/L, respectively. Following the level of the treatment in the Moving Bed Biofilm Reactor (MBBR) unit, a notable reduction in these parameters was achieved, indicating
the system’s ability to degrade organic pollutants efficiently [32]. For instance, in MBBR1, CODt and BOD5 concentrations decreased to 41.7 mg/L and 15.2 mg/L, respectively, reflecting substantial removal efficiency.

Moreover, the treatment process demonstrated effective removal of suspended solids, as evidenced by the significant reduction in turbidity levels from 31.9 FNU in graywater to 16.2 before the filtration, which represented 50% and later to 1.4 FNU in the treated water after filtration and UV disinfection. This indicates successful filtration and clarification processes within the treatment system.

Nutrient removal, particularly phosphate and ammonium, is crucial for preventing eutrophication in receiving water bodies [33]. The inlet graywater is considered graywater (light type) [34] with deficient concentrations of phosphate and ammonium, which is not in this case so relevant to discuss the efficacy of the MBBR elimination and results, although we can see the nitrification took place. As well as for the TSS, where a big part of the elimination rate is due to the filter capacity.

Overall, these results demonstrate the treatment system’s effectiveness at Pilot 1 in significantly improving the quality of graywater and producing treated water that meets regulatory standards (Table 3) for discharge or potential reuse applications [1].

### Table 3. Quality requirements for treated wastewater and graywater in Germany [35] and other countries [36] for domestic irrigation reuse.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Germany</th>
<th>Australia</th>
<th>Jordan</th>
<th>Spain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types of water</td>
<td>Treated graywater</td>
<td>Treated graywater</td>
<td>Treated wastewater</td>
<td>Treated wastewater</td>
</tr>
<tr>
<td>pH</td>
<td>NR</td>
<td>NR</td>
<td>6.5–9</td>
<td>NR</td>
</tr>
<tr>
<td>Turbidity</td>
<td>&lt;2 NTU</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>TSS</td>
<td>NR</td>
<td>&lt;10 mg/L</td>
<td>&lt;50 mg/L</td>
<td>&lt;10 mg/L</td>
</tr>
<tr>
<td>BOD5</td>
<td>&lt;5 mg/L</td>
<td>&lt;10 mg/L</td>
<td>&lt;30 mg/L</td>
<td>NR</td>
</tr>
<tr>
<td>COD</td>
<td>NR</td>
<td>&lt;100 mg/L</td>
<td>NR</td>
<td>&lt;100 mg/L</td>
</tr>
<tr>
<td>E. coli</td>
<td>&lt;10,000/100 mL</td>
<td>NR</td>
<td>&lt;10,000/100 mL</td>
<td>0/100 mL</td>
</tr>
</tbody>
</table>

### Table 4. The average concentration values. The number of samples analyzed for each category is specified (graywater storage: n = 20; treated wastewater storage: n = 20), allowing for a statistically meaningful assessment of the treatment system’s efficacy.

<table>
<thead>
<tr>
<th>Parameters/Sample</th>
<th>CODt [mg/L]</th>
<th>CODs. [mg/L]</th>
<th>BOD5 [mg/L]</th>
<th>TSS 0.45 μm Original [mg/l]</th>
<th>Phosphate/OrthoPO4-P [mg/L]</th>
<th>Turbidity [FNU]</th>
<th>Ammonium NH4-N [mg/L]</th>
<th>Nitrate NO3-N [mg/L]</th>
<th>Temperature (°C)</th>
<th>Dissolved Oxygen [mg/L]</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graywater</td>
<td>122.4</td>
<td>76</td>
<td>69</td>
<td>29.3</td>
<td>0.1</td>
<td>31.9</td>
<td>2.3</td>
<td>0.75</td>
<td>25.4</td>
<td>4.1</td>
<td>8</td>
</tr>
<tr>
<td>Graywater Tank</td>
<td>104.3</td>
<td>63</td>
<td>51.8</td>
<td>24.4</td>
<td>0.3</td>
<td>73.9</td>
<td>8.3</td>
<td>0.3</td>
<td>24.2</td>
<td>1.03</td>
<td>7.3</td>
</tr>
<tr>
<td>MBBR2</td>
<td>41.7</td>
<td>19.4</td>
<td>35.2</td>
<td>18.8</td>
<td>0.2</td>
<td>16.2</td>
<td>0.6</td>
<td>6.9</td>
<td>24.1</td>
<td>5.5</td>
<td>8.2</td>
</tr>
<tr>
<td>Treated water</td>
<td>19.8</td>
<td>17.9</td>
<td>3.6</td>
<td>0.25</td>
<td>0.21</td>
<td>1.4</td>
<td>0.1</td>
<td>7.1</td>
<td>22.2</td>
<td>6.9</td>
<td>7.8</td>
</tr>
</tbody>
</table>

### 3.2. Treatment Plant in Pilot 2

The presented results (Table 5) pertain to the analysis of water quality parameters within the treatment plant located at Pilot 2, with a different graywater inlet characteristic than the inlet in the previous MBBR system in Section 3.1.

Initially, the average concentrations of various parameters in the graywater stream indicated relatively elevated organic matter levels. In this case study, the chemical oxygen demand (CODt) and biochemical oxygen demand (BOD5) average concentrations of 359.6 mg/L and 126.9 mg/L, respectively.
Table 5. The average concentration values. The number of samples analyzed for each category is specified (graywater storage: n = 18; treated wastewater storage: n = 20; drinking water: n = 10), allowing for a statistically meaningful assessment of the treatment system’s efficacy.

When looking into the elimination rate and the effectiveness of the MBBR treatment system, we have an elimination rate of 90–85% for CODt, 98% for BOD5, TSS, turbidity, and NH4+. This is a very encouraging result, but to understand and look into the optimization possibilities, it is important to look into the elimination rates in each of the treatment levels.

Upon treatment in the Moving Bed Biofilm Reactor (MBBR) units, considerable increasing values in pollutant concentrations were observed. Notably, MBBR2 represents level 2 in the treatment. These values were later lightly decreased with a rate of 12–19% for CODt from MBBR3 to MBBR5 and an almost 30% elimination rate for BOD5. The nitrification took place at that stage as well as the treatment, with a reduction of 98% of the initial NH4+ concentration. Although the initial concentration of phosphate is relatively low, the elimination took place in the early stage in MBBR3, with an elimination rate of 98%.

Comparatively, the quality of the treated water approached that of potable drinking water, with pollutant concentrations significantly lower than those observed in the graywater stream. This underscores the treatment system’s effectiveness in producing high-quality effluent suitable for various reuse applications.

Overall, the results underscore the efficacy of the treatment plant at Pilot 2 in improving water quality and mitigating pollution, thus contributing to environmental sustainability and resource conservation efforts.

3.3. Treatment Plant in Pilot 3

Table 6 presents the graywater characterization obtained in Pilot 3 with different graywater inlet characteristics compared to the graywater characteristics in Sections 3.1 and 3.2. The graywater here is known as type heavy [34].

Table 6. The average concentration values. The number of samples analyzed for each category is specified (graywater storage: n = 20; treated wastewater storage: n = 20), allowing for a statistically meaningful assessment of the treatment system’s efficacy.
Initially, the analysis of graywater revealed elevated concentrations of organic matter compared to the previous Pilots 1 and 2, particularly in terms of chemical oxygen demand (CODt), biochemical oxygen demand (BOD5), and suspended solids (TSS 0.45 µm original). The average CODt concentration was notably high at 492.5 mg/L, indicating a substantial organic load present in the graywater. Similarly, BOD5 levels were elevated at 248.7 mg/L, underscoring the biodegradable organic matter content within the influent stream. Furthermore, suspended solids were prevalent, with an average concentration of 167.7 mg/L, highlighting the need for effective treatment measures to mitigate pollutant discharges.

Following treatment within the Moving Bed Biofilm Reactor (MBBR) units, significant reductions in pollutant concentrations were observed. Moreover, the treatment procedure has facilitated the gradual removal of nutrients, showcasing a progressive alleviation at distinct stages within the graywater treatment regimen. Initial observations at the MBBR2 treatment level unveil an influent composition characterized by CODt at 15%, accompanied by BOD5 at 14%, alongside an incipient phase of nitrification, denoted by NH4+ at approximately 10%. Transitioning to the subsequent treatment stage, which serves as the focal point for remediation, substantial removal efficiencies are discerned. Herein, the treatment regimen manifests a noteworthy elimination rate, witnessing a decline in CODt by 75%, BOD5 by 85%, and significant reduction rates within the TSS, amounting to 57% for CODt, 38% for turbidity, and an impressive 99% for NH4+.

Delving deeper into the treatment cascade, the third stage (sedimentation), as depicted in this case study, incorporates a decantation process preceding filtration, thus culminating in a further augmentation of removal rates. This stage showcases a heightened efficacy, evidenced by a notable enhancement in removal efficiencies, including a substantial decline in CODt by 90%, BOD5 by 98%, and remarkable removal rates within the TSS, achieving 92% for CODt, 90% for turbidity, and complete elimination (100%) for NH4+. Notably, the pinnacle of nutrient removal efficacy is observed at the sedimentation tank reactor level, wherein NH4+ is entirely eradicated, thereby underscoring the robustness and effectiveness of the treatment system in achieving comprehensive nutrient remediation.

4. General Discussion

The three case studies presented describe the performance of graywater treatment plants located in Berlin, namely Pilot 1, Pilot 2, and Pilot 3, each treating graywater with different characteristics. Graywater, which comes from activities such as bathing, washing clothes and hands, and cooking, makes up a significant proportion of domestic wastewater and represents a valuable resource for reuse after appropriate treatment [37].

In Pilot 1, the treatment plant handles graywater from showers only in a residential building with two reactors representing two treatment stages. Analysis of the graywater characteristics revealed low levels of organic matter [38], with a presence of suspended solids and nutrients that exceeded reuse standards [39], necessitating treatment.

However, with the application of a Moving Bed Biofilm Reactor (MBBR) system, substantial reductions in pollutant concentrations have been achieved, demonstrating the effectiveness of the treatment process in improving water quality, with removal rates exceeding 95% for some parameters such as BOD5, TSS, turbidity, and ammonium. Treated water from Pilot 1 showed notable improvements, meeting regulatory standards for potential reuse applications such as toilet flushing and urban gardening [40].

Similarly, the Pilot 2 wastewater treatment plant treats graywater from domestic activities such as showering, hand washing, and the washing machine of a residential complex. Analysis of the graywater revealed a moderate level of organic matter, requiring effective treatment strategies [41].

In contrast, the treatment plant in Pilot 3 addresses graywater from another residential area, employing MBBR units for treatment [42]. The analysis of graywater characteristics revealed higher levels of organic matter than the other case studies. However, through the application of appropriate treatment measures, including biological degradation and decantation before the filtration processes, significant improvements in water quality were
achieved. The treated water from Pilot 3 met regulatory standards for reuse in non-potable applications [45], indicating the treatment system’s effectiveness in producing clean and safe effluent.

The examination of three distinct case studies serves to underscore the efficacy of treatment systems in managing graywater within urban settings and underscores the potential for graywater reuse after treatment. Each case study presents variations in the characteristics and volume of graywater inflow, all of which have been subjected to treatment utilizing the same technology, namely the MBBR system, to meet the requisite standards for water reuse for non-potable applications. It is imperative to delve into the reasons behind the observed higher efficiency at the primary treatment level, as well as the relatively insignificant disparity in elimination rates across different reactors in two case studies, which only becomes pronounced post-filtration, but the different levels are important to ensure the denitrification process [44]. This prompts a deeper analysis of the factors influencing treatment performance, the dynamics of nutrient removal within the MBBR system, and the possibilities to optimize the treatment systems.

Comparing the three pilot systems is crucial to understanding that optimization depends on the nature and characteristics of the incoming graywater. Equally important is comparing the effectiveness of the MBBR system with other graywater treatment systems, as outlined in Table 1 of the introduction. The efficiency of the MBBR systems analyzed in this study demonstrates that they are more effective compared to other systems examined and grouped in a study [20,39,45] that compares various biological, chemical, or physical treatment methods.

Overall, the three case studies underscore the importance of implementing efficient treatment processes for graywater management. By treating graywater from different sources, these treatment plants not only mitigate pollution but also contribute to water conservation efforts by enabling the reuse of treated water for non-potable purposes [21]. The successful implementation of treatment technologies such as MBBR systems demonstrates the feasibility of sustainable water management practices in residential settings, promoting environmental sustainability and resource conservation.

The key point to highlight is that Moving Bed Biofilm Reactor (MBBR) treatment technology, as applied in the various cases examined in this study, represents a sustainable approach that yields significant environmental returns. For instance, the Block 6 or Pilot 3 plant has been operational since 2006. Despite undergoing recent renovations, it has consistently functioned on the same foundational principles for the past 18 years. However, to ensure the maintenance of high treatment standards, regular upkeep is essential. This includes the UV lamps utilized for disinfection, which have a lifespan of 8000 h and, in Block 6, necessitate replacement every 1 to 4 years. Additionally, in all pilots, the treated water consistently exhibited E. coli levels of less than 10 CFU per 100 mL.

5. Conclusions

In conclusion, this scientific study presents a comprehensive assessment of treatment plants located in distinct residential settings, namely Pilot 1, Pilot 2, and Pilot 3, each treating graywater from various sources. The novelty of this study lies in its provision of empirical data and insights into the performance of treatment systems under real-world conditions, thereby serving as a living laboratory for evaluating the efficacy of graywater treatment technologies.

Through rigorous analysis of graywater characteristics and treated effluent quality, this study elucidates the effectiveness of treatment processes, particularly the application of Moving Bed Biofilm Reactor (MBBR) systems, in nutrient removal and improving water quality. The results demonstrate significant reductions in pollutant concentrations, including organic matter, suspended solids, and nutrients, across all case studies, highlighting the efficiency of the treatment processes deployed.

Furthermore, the study contributes to the establishment of a valuable database encompassing different quality levels of inlet graywater, thereby facilitating further research and
development in the field of graywater management. By providing empirical evidence and real-world data, this study serves as a valuable resource for researchers, policymakers, and practitioners seeking to implement sustainable water management practices.

Overall, this study underscores the importance of addressing graywater management challenges in residential settings and highlights the feasibility of employing advanced treatment technologies such as MBBR systems to achieve water conservation and resource efficiency objectives. Moving forward, continued research and innovation in graywater treatment and optimizations are essential for promoting environmental sustainability and mitigating the impact of urbanization on water resources.

However, while the study provides valuable data and insights, several limitations and areas for improvement warrant consideration. Firstly, the study focuses solely on residential settings, limiting the generalizability of the findings to other contexts such as commercial or industrial applications. Future research could explore the performance of treatment technologies in a broader range of settings to provide a more comprehensive understanding of their efficacy.

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References
4. Akpan, V.E. Assessing the public perceptions of treated wastewater reuse: Opportunities and implications for urban communities in developing countries. Helion 2020, 6, e05246. [CrossRef]


43. Ultrafiltration as Tertiary Treatment for Municipal Wastewater Reuse—ScienceDirect. Available online: [https://www.sciencedirect.com/science/article/pii/S1383586621006328?casa_token=6FZmF6nW1moAAAAA:MjYdRlTgR7EW01-eI5FTsQR09-Gl7AB-ScEtNzGjKgbU6bx1rPllHygVHF6h5Si2LrpjLjDUZ6Q](https://www.sciencedirect.com/science/article/pii/S1383586621006328?casa_token=6FZmF6nW1moAAAAA:MjYdRlTgR7EW01-eI5FTsQR09-Gl7AB-ScEtNzGjKgbU6bx1rPllHygVHF6h5Si2LrpjLjDUZ6Q) (accessed on 28 March 2024).


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