membranes

Article

Assessment of a Low-Cost Ceramic Membrane Bioreactor for Treating Real Hospital Wastewater: Applications in Small Healthcare Facilities

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Abstract

This study presents one of the first laboratory-scale evaluations of a low-cost ceramic membrane bioreactor (LCMBR) for treating real hospital wastewater. The system employed a locally fabricated ceramic membrane integrated with a biological reactor to achieve simultaneous biological degradation and membrane filtration. The study monitored key water quality parameters, including chemical oxygen demand (COD), biochemical oxygen demand (BOD5), suspended solids (SS), nitrogen species, phosphate (PO4-P), and 15 selected heavy metals, to assess treatment efficiency. The LCMBR achieved more than 80% removal of organic pollutants, reducing effluent COD and BOD to less than 15 mg L^{-1} and 10 mg L^{-1}, respectively. The LCMBR achieved ~60–70% of total inorganic nitrogen and moderate (40–60%) phosphorus removal, primarily through biological assimilation and adsorption. Changes in inorganic nitrogen and phosphate concentrations indicated partial nutrient removal, although the specific nitrogen and phosphorus transformation pathways were not directly established. The LCMBR system effectively removed fifteen trace metals, including Al, V, Cr, Mn, Fe, Co, Ni, Zn, Cu, Cd, As, Mo, Pb, Sb, and Ba, through adsorption onto the biomass. The treated effluent quality was well below the recommended international discharge standards. Membrane flux declined during the final part of the experimental period and recovered after physical cleaning. A preliminary engineering assessment for a hypothetical decentralized treatment facility with a design capacity of 10 m^{-3} d^{-1} estimated an energy requirement of approximately 0.133 kWh m^{-3} under the specified assumptions. The LCMBR offers a cost-effective and sustainable option for decentralized hospital wastewater treatment.

Keywords: hospital wastewater; low-cost treatment; low-cost ceramic membrane bioreactor (LCMBR); pollutant removal; decentralized system

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1. Introduction

Sustainable urban development, driven by rapid urbanization, poses critical waste-

water management challenges due to increasing wastewater generation and infrastructure constraints [1]. Hospital wastewater (HWW) is among the most complex and hazardous types of wastewater, posing significant risks to public health and aquatic environments if discharged without adequate treatment [2]. HWW is generated from various healthcare activities, including patient care, diagnostic procedures, laboratory operations, and routine cleaning and disinfection practices [3]. Consequently, HWW contains higher concentrations of organic matter, nutrients, and toxic heavy metals than conventional domestic wastewater [2,4]. High levels of chemical oxygen demand (COD) and biochemical oxygen demand (BOD) are common due to biodegradable organic compounds, pharmaceuticals, body fluids, and other healthcare-related wastes. In addition, HWW often contains high concentrations of nitrogenous and phosphorus compounds from human excreta, medical activities, and cleaning agents [4,5].

Furthermore, toxic heavy metals such as chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd), and arsenic (As) may enter HWW through diagnostic reagents, laboratory chemicals, pharmaceuticals, and corrosion of plumbing systems [2,6]. These metals are of particular environmental concern because of their toxicity, persistence, potential for bioaccumulation, and adverse effects on aquatic ecosystems and human health, even at low concentrations. The BOD-to-COD ratio, commonly referred to as the biodegradability index, is generally lower in HWW compared to municipal wastewater, indicating reduced biodegradability and greater resistance to conventional biological treatment processes [7]. Consequently, HWW poses significantly greater environmental and public health risks than domestic wastewater due to its complex mixture of organic pollutants, nutrients, heavy metals, and other healthcare-related contaminants [8]. Therefore, effectively removing organic matter, nutrients, and toxic heavy metals is essential to minimize the environmental impacts and health risks associated with discharging untreated or inadequately treated HWW.

HWW management is particularly challenging in many developing countries, where centralized wastewater treatment infrastructure may be limited or inadequate [4,9]. In practice, HWW is frequently mixed with domestic sewage and discharged directly into municipal sewer systems for co-treatment at the centralized facilities [10]. As conventional municipal wastewater treatment plants are not designed to handle the complex matrix of medical effluents, operational inadequacies often result in the release of hazardous pollutants, particularly heavy metals and recalcitrant compounds, into aquatic environments, frequently exceeding safe discharge limits. Over the years, several treatment technologies have been proposed and employed, including the activated sludge process, membrane bioreactors (MBRs), moving bed biofilm reactors, and the Fenton process [11,12]. Among these technologies, MBRs have emerged as a superior solution, combining biological degradation with physical separation to produce high-quality effluent [13].

From a technological perspective, MBRs can operate at high mixed liquor suspended solids (MLSS) concentrations, enhancing biodegradation efficiency and making them particularly suitable for treating complex wastewaters such as hospital effluents [13]. Operating MBRs under low organic load (low COD) maintains a balanced F/M ratio, and reduces the formation of soluble microbial products (SMPs) and extracellular polymeric substances (EPSs), thereby minimizing membrane fouling [14–16]. Several studies have demonstrated that the organic loading rate (OLR) and the food-to-microorganism (F/M) ratio significantly influence MBR performance and membrane fouling. Alotaibi et al. [17] investigated the effects of OLR and F/M ratio on COD removal efficiency. They recommended an F/M ratio ≤ 0.33 g COD g^{-1} MLSS d^{-1} for optimal MBR performance. A comprehensive review by Iorhemen et al. [15] reported that lower F/M

ratios are generally preferable, as higher F/M conditions promote increased EPS production and membrane fouling, which can indirectly impair COD removal efficiency. Similarly, Al-Sayed et al. [14] demonstrated that high F/M conditions adversely affect COD removal efficiency and hinder nitrification processes in MBR systems. Importantly, the removal of bulk organic matter, as indicated by reductions in COD and BOD, does not necessarily demonstrate the effective elimination of individual pharmaceutical compounds or other emerging micropollutants in HWW. These contaminants may exhibit compound-specific biodegradation pathways and persist in treated effluents even when conventional organic pollution indicators show substantial reductions. Recent research has highlighted the importance of investigating microbial degradation mechanisms to understand how individual organic contaminants transform and are removed [18].

Recently, researchers developed a low-cost ceramic membrane (LCM) as an alternative to expensive polymeric membranes [19]. Locally and readily available materials, namely clay soil and rice bran, were used for the fabrication of this LCM [20]. The developed LCM was subsequently integrated into MBR systems and applied to various wastewater treatment scenarios, including synthetic greywater, synthetic wastewater, and real septic tank wastewater [21–23]. Alresheedi et al. [21] designed a lab-scale LCM bioreactor (LCMBR) for decentralized wastewater treatment. They evaluated its performance for treating domestic wastewater from septic tanks in small communities in the Kingdom of Saudi Arabia (KSA). The LCMBR efficiently removed BOD, COD, total suspended solids (TSS), and ammonia (NH3). Recently, Haider et al. [24] conducted a life cycle assessment of the LCMBR system for decentralized wastewater treatment in smaller communities and demonstrated its clear superiority over conventional wastewater transport to centralized facilities across most impact categories. These results indicate that LCMBR technology has strong potential as an effective and sustainable decentralized treatment option for on-site treatment of small-sized HWW.

Small healthcare facilities, including community hospitals, primary healthcare centers, private clinics, and rural medical facilities, often generate relatively low wastewater volumes but may lack on-site treatment systems due to financial and technical constraints [13]. Conventional membrane bioreactors (MBRs) provide excellent treatment performance; however, their widespread application in decentralized settings is often limited by the high cost of commercial membranes, intensive maintenance requirements, membrane fouling, and relatively high energy consumption [15,25]. In contrast, LCMBRs offer several advantages that make them particularly suitable for decentralized HWW treatment. Membranes can be fabricated from inexpensive, locally available materials, reducing capital costs and dependence on imported products [21]. Relatively low fouling tendency and simple cleaning procedures also reduce operational complexity and maintenance requirements, making the technology suitable for facilities with limited technical expertise [21,23]. Furthermore, the low energy demand and compact footprint of LCMBR systems enhance their economic feasibility for small-scale applications. These characteristics make LCMBR technology a promising, sustainable solution for decentralized HWW treatment, particularly in developing countries and small communities in arid regions where affordable, reliable wastewater management systems are urgently needed.

Although researchers have investigated locally fabricated ceramic membrane bioreactors for greywater, domestic wastewater, and septic tank effluent treatment [21–23], their performance under the complex chemical conditions of real hospital wastewater remains insufficiently characterized. Hospital wastewater differs from conventional domestic wastewater because of its variable organic composition, elevated nutrient concentrations, and potential occurrence of multiple trace metals originating from healthcare

activities, laboratory operations, and hospital infrastructure. The present study therefore does not develop a new LCMBR configuration but instead experimentally evaluates an established low-cost ceramic membrane technology using real hospital wastewater. In particular, the study simultaneously examines organic matter removal, changes in inorganic nitrogen and phosphorus concentrations, and the behavior of 15 selected trace metals during a 30-day laboratory-scale operation. The investigation also examines operational characteristics, including permeate flux, biomass concentration, and membrane cleaning events. It provides an engineering-based preliminary assessment of energy requirements and membrane costs for a hypothetical decentralized healthcare facility.

The findings are intended to provide preliminary experimental evidence regarding the applicability of LCMBR technology to real hospital wastewater rather than demonstrate long-term or full-scale treatment performance. Accordingly, the objectives of this study are to: (i) evaluate the removal performance of organic matter in real hospital wastewater; (ii) quantify changes in inorganic nitrogen and phosphate concentrations during LCMBR operation; (iii) assess the concentration changes of 15 selected trace metals between influent and treated effluent; and (iv) investigate the operational behavior of the LCMBR and estimate its potential energy and membrane-related costs under a representative decentralized treatment scenario.

2. Materials and Methods

2.1. HWW Source and Sampling

The Qassim University Medical City (University Hospital), located in Buraydah, Al-Qassim Region, KSA, was selected as the HWW source for this study. This new central hospital, in its initial stages of reaching full operational capacity, reflects the characteristics of a basic-level, fully operational, small-sized healthcare facility serving a smaller community in KSA. To obtain representative wastewater samples, the hospital sewerage network was carefully examined to identify a sampling location that received the combined effluent from all hospital activities. Based on this assessment, we selected the final manhole immediately upstream of the discharge point to the municipal sewer network as the primary sampling point. This manhole collects wastewater from all hospital departments, including inpatient wards, outpatient clinics, laboratories, diagnostic units, administrative facilities, and supporting services, thereby representing the overall hospital effluent.

Wastewater samples were collected weekly over a 30-day operational period using clean high-density polyethylene containers with a total collection volume of approximately 200 L per sampling event, sufficient to operate the LCMBR. The sampling program was designed to represent routine weekday hospital operation, during which patient occupancy, laboratory activities, and cleaning operations are relatively stable. We did not include weekend sampling because hospital activities differ substantially on weekends. Consequently, the present results represent typical weekday operating conditions and should not be interpreted as fully representing seasonal or weekend variations. We immediately transported the collected wastewater to the laboratory and stored it under appropriate conditions before using it in the experimental system. Before sampling, we thoroughly washed all containers with detergent and rinsed them with deionized water to avoid contamination. Sampling on weekends was avoided to ensure collection of representative HWW generated during normal hospital operations. Grab samples were collected directly from the flowing wastewater stream within the final manhole serving the hospital departments to obtain representative influent wastewater. One grab sample was collected on each sampling day. Following collection, the samples were tightly sealed, properly labeled, and transported to the Environmental Engineering

Laboratory at Qassim University. Approximately 1–2 L of HWW was retained for physicochemical analysis and stored at 4 °C until analysis. The remaining wastewater was transferred to the LCMBR influent tank, where it was stored under continuous stirring at room temperature to maintain homogeneity and prevent solids settling during reactor operation.

2.2. Low-Cost Ceramic Membrane (LCM)

The LCM was manufactured using locally sourced materials, including soil (clay) and rice bran. The manufacturing methodology followed the previous study [20] in detail. The membrane is cylindrical, with a height of 100 mm and internal and external diameters of 60 mm and 100 mm, respectively, providing a total filtration surface area of 390 cm^2 (0.039 m^2). The pore size ranges from 1 to 5 μm, and the ceramic filters exhibit a porosity of 60–65%. Scanning electron microscopy coupled with energy-dispersive X-ray spectrometry analysis confirmed the presence of several elements, including C, O, Si, Fe, and Al, in the fired ceramic filters [26]. The estimated material and fabrication cost was approximately US$0.2–0.3 per membrane unit under laboratory-scale production conditions, making it a cost-effective and sustainable alternative to conventional commercial membranes.

2.3. LCMBR Configuration and Experimental Setup

Figure 1 shows the detailed configurations of the LCMBR system used in this study. The LCMBR system comprised a feed tank (capacity of 300 L) (model no. HM 162.20, GUNT, Germany), with two stirring propellers (model no. CE 701, Germany), followed by an aeration tank with a capacity of 40 L, and a collection tank with a capacity of 40 L (plastic bucket). A feed pump (model no. HM 365.24, GUNT, Germany) pumped raw wastewater from the feed tank to the aeration tank. A flow meter (model no. GEMO 55/1/11, Germany) monitored and controlled the feed rate. An LCMBR was installed in the aeration tank as an alternative to a commercial membrane to develop the LCMBR.

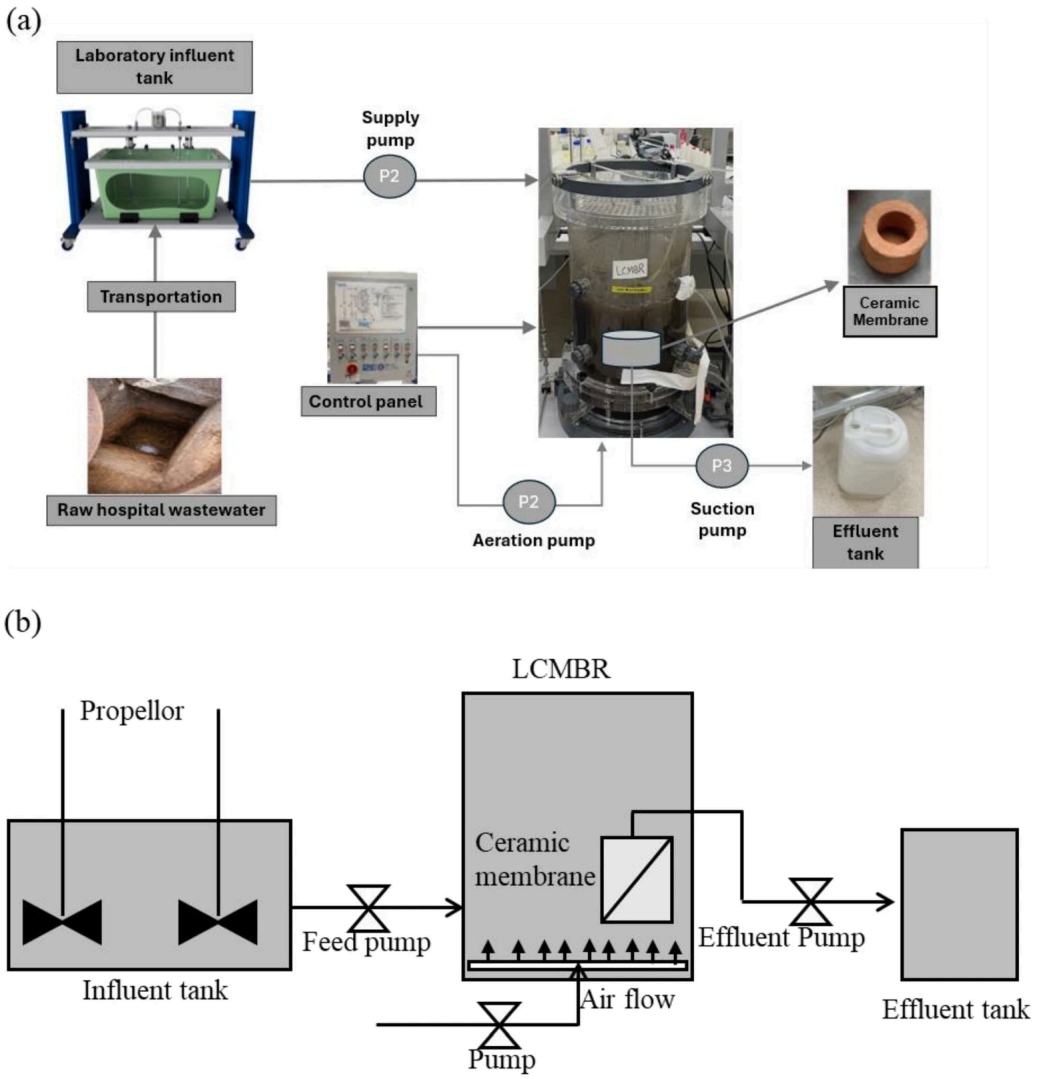

Figure 1. Configuration of the low-cost ceramic filter: (**a**) pictorial view of the fabricated membrane, and (**b**) schematic diagram illustrating the system in detail.

The LCMBR was seeded with 16 L of activated sludge collected from the Buraydah wastewater treatment plant, which treats domestic wastewater at 150,000 m^3 d^{-1}. The initial mixed liquor suspended solids (MLSS) concentration was approximately 3845 mg/L. The LCMBR was operated at a nominal solids retention time (SRT) of 280 days, calculated as the ratio of the reactor working volume (40 L) to the average daily sludge withdrawal volume. Approximately 1 L of mixed liquor was withdrawn weekly for sludge wasting, corresponding to an average withdrawal rate of 0.143 L d^{-1}. Assuming negligible solids loss through the permeate and a sludge concentration comparable to that of the reactor mixed liquor, the SRT was estimated to be 280 days (40 L/0.143 L d^{-1}). The membrane was operated at an initial permeate flux of approximately 20 L m^{-2} h^{-1}, corresponding to a theoretical permeate production rate of 19.2 L d^{-1} for the membrane surface area of 0.04 m^2. Based on the 40 L reactor working volume, this represented an initial hydraulic retention time (HRT) of approximately 2.08 days. However, permeate flux gradually declined during operation due to membrane fouling, reducing actual permeate production and increasing effective HRT. We determined the flux decline from daily permeate production measurements, as we monitored and recorded permeate volume daily throughout the experimental period. Accordingly, we calculated the actual HRT based on the reactor working volume and the corresponding measured daily permeate

production, rather than assuming a constant nominal flow throughout the experiment. We applied continuous aeration at the reactor bottom at 9.6 ± 2.7 L min^{-1} to maintain dissolved oxygen (DO) at an average of 7.4 mg L^{-1}, ensuring complete mixing of the biomass and providing sufficient DO for microbial metabolic activities. Airflow was monitored using an airflow meter (model no. GEMO 75/1/14,Barsbüttel, Germany). All hydraulic parameters, including flux and hydraulic retention time (HRT), are detailed in Table 1. Samples of feed water, treated water, and mixed liquor from the treatment system were collected regularly and analyzed to assess their physical and chemical properties.

Table 1. LCMBR operating and reactor parameters.

	Parameters (n = 30)	Mean ± SD
LCMBR operating parameters	Flux (L $m^{-2}.h^{-1}$)	20 ± 4.5
	HRT (d)	2.0 ± 0.9
	SRT (d)	280
	Aeration mode	Continuous
	Aeration rate (L min^{-1})	9.6 ± 2.7
	COD loading (g COD m^{-3} d^{-1})	60 ± 17
	BOD loading (g BOD m^{-3} d^{-1})	25 ± 3.0
	Bacterial Inoculation	16 L of activated sludge (3845 mg L^{-1} MLSS)
LCMBR reactor parameters	Effective reactor volume (L)	40
	Ceramic membrane area (m^2)	0.04
	Pore size (μm)	1–5
	Reactor pH	8.57 ± 0.46
	DO (mg L^{-1})	7.4 ± 0.3
	Temperature (°C)	21.0 ± 0.6
	MLSS (mg L^{-1})	3845 ± 250
	F/M ratio (g BOD g^{-1} MLSS d^{-1})	0.008 ± 0.001

2.4. Analytical Methods

Water quality parameters were analyzed for raw HWW (influent), reactor wastewater, and treated HWW (effluent) to assess the LCMBR's treatment efficiency. The measured water quality parameters included pH, DO, temperature, turbidity, TSS, MLSS for sludge, COD, BOD5, ammonia (NH_3), nitrate (NO_3), nitrite (NO_2), and phosphate (PO4-P). Common metals, including aluminum (Al), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), zinc (Zn), copper (Cu), cadmium (Cd), arsenic (As), molybdenum (Mo), lead (Pb), antimony (Sb), and barium (Ba), were also analyzed. An HQ40d HACH portable meter (HACH,Loveland, CO, USA) measured pH and DO, and a HACH turbidity meter measured turbidity. SS and MLSS were analyzed by the gravimetric method, and COD analysis was conducted using HACH COD cuvettes and a COD reactor (HACH LT200,Loveland, CO, USA). We measured 5 d BOD using the incubation method. HACH standard powder pillow methods were used to measure NO_3, NO_2, NH_3, and PO_4-P using a HACH DR3900 spectrophotometer (HACH,Loveland, CO, USA). Heavy metals were analyzed using Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) (Agilent 7800 ICP-MS, Agilent Technologies, Santa Clara, California,USA).

Influent metal samples were subjected to acid digestion using HF (48–49% *w*/*w*),

HNO_3 (65–70% *w*/*w*), and H_2O_2 (30% *w*/*w*) to facilitate the dissolution of particulate-associated metals before ICP-MS analysis. In contrast, effluent samples were acidified with concentrated HNO_3 without additional digestion because the collected membrane permeate appeared visually clear, with no apparent suspended particles. Acidification preserved the samples before ICP-MS analysis. Therefore, the sample-preparation procedures differed between influent and effluent samples and may have resulted in differences in metal recovery, particularly for particulate-associated metals. We considered this analytical distinction when interpreting the measured changes in metal concentrations. The reported influent and effluent concentrations represent total metal concentrations, including both dissolved and particulate-associated fractions. We calibrated the instrument using multi-element standard solutions, and calibration curves showed excellent linearity, with correlation coefficients (R2) ranging from 0.994 to 0.999. Quality assurance and quality control procedures included calibration verification standards, procedural blanks, and triplicate analyses. Recovery values ranged between 90 and 108%, and relative standard deviations remained below 5%. The method detection limits for the target metals were as follows: Al (0.07 μg L^{-1}), V (0.002 μg L^{-1}), Cr (0.05 μg L^{-1}), Mn (0.03 μg L^{-1}), Fe (0.5 μg L^{-1}), Co (0.02 μg L^{-1}), Ni (0.15 μg L^{-1}), Cu (0.06 μg L^{-1}), Zn (0.3 μg L^{-1}), As (0.03 μg L^{-1}), Mo (0.01 μg L^{-1}), Pb (0.2 μg L^{-1}), Cd (0.007 μg L^{-1}), Sb (0.004 μg L^{-1}), and Ba (0.025 μg L^{-1}).

For ICP-MS analysis, we measured each prepared sample in triplicate under identical analytical conditions to assess instrumental repeatability. These triplicate measurements represent technical replicates rather than independent wastewater samples. Accordingly, technical replicate variability is distinguished from temporal variability among independent sampling events. The number of observations varied by parameter because sampling and analytical frequencies differed. We collected influent wastewater during weekly sampling events, whereas we monitored selected operational and effluent parameters more frequently during the 30-day experimental period. The sample size (n) for each parameter is therefore reported individually in the corresponding tables and figures. Furthermore, the treatment experiments were conducted using a single LCMBR reactor; therefore, independent reactor-level replication was not performed. We acknowledged this limitation when interpreting treatment performance and assessing the broader applicability of the findings.

3. Results

3.1. Wastewater Characteristics

Table 2 summarizes the characteristics of the collected HWW. The pH was slightly alkaline (8.7), likely due to alkaline cleaning agents, detergents, and disinfectants used in hospital facilities. The relatively low DO of 4.1 mg L^{-1} indicates oxygen-consuming organic matter, leading to partial oxygen depletion in the wastewater before treatment. SS and turbidity were comparatively low, measuring 30 mg L^{-1} and 39 NTU, respectively, indicating that the HWW contained limited particulate and colloidal material. Organic pollution, as measured by COD (139 mg L^{-1}) and BOD (56 mg L^{-1}), was low to moderate and significantly lower than values commonly reported for HWW [5]. However, some studies have also reported low organic pollution in HWW [27]. The BOD/COD ratio of 0.41 indicates partial biodegradability; therefore, biological treatment processes could effectively remove a substantial fraction of the organic load.

Table 2. Characteristics of hospital wastewater used in this study, LCMBR operation, and reactor parameters.

Parameters (n = 12)	Mean ± SD	Heavy Metals (n = 4)	Mean ± SD
* pH (range)	9.3 ± 0.48	Al (mg L^{-1})	12 ± 0.03
* DO (mg L^{-1})	4.1 ± 1.9	V (µg L^{-1})	12 ± 2.93
* Temperature (0 C)	21.0 ± 0.64	Cr (µg L^{-1})	296 ± 5
SS (mg L^{-1})	30 ± 2	Mn (µg L^{-1})	211 ± 1
Turbidity (NTU)	39.8 ± 13.6	Fe (mg L^{-1})	67 ± 1
COD (mg L^{-1})	140 ± 49	Co (µg L^{-1})	14 ± 0.84
BOD5 (mg L^{-1})	60 ± 7	Ni (µg L^{-1})	1014 ± 4.53
NH_3-N (mg L^{-1})	43 ± 9	Cu (µg L^{-1})	381 ± 38.59
NO_3-N (mg L^{-1})	4.3 ± 1.2	Zn (µg L^{-1})	934 ± 93.54
NO_2-N (mg L^{-1})	0.6 ± 1.1	As (µg L^{-1})	1112 ± 1.46
PO_4-P (mg L^{-1})	44 ± 22	Mo (µg L^{-1})	154 ± 2.55
		Pb (µg L^{-1})	76.43 ± 12.48
		Cd (µg L^{-1})	32 ± 1.53
		Sb (µg L^{-1})	25 ± 4.49
		Ba (µg L^{-1})	165.67 ± 136.09

* indicate n=30

Nevertheless, the relatively low COD and BOD classify this HWW as low-strength wastewater, which may limit biomass growth and necessitate adjustment of the F/M ratio in biological treatment systems. Ammonia (NH_3-N) was measured at 43.5 mg L^{-1} and was the predominant nitrogen species in the HWW, while nitrate (NO_3-N) and nitrite (NO_2-N) concentrations were low at 4.3 mg L^{-1} and 0.6 mg L^{-1}, respectively. These results indicate that HWW experienced limited aeration and short HRT in the sewer system before sampling. Elevated ammonia levels are of concern because of their potential toxicity to aquatic organisms and their oxygen demand during biological oxidation. Phosphate concentrations were relatively high (67 mg L^{-1}), reflecting substantial nutrient loading from hospital detergents and cleaning agents. High phosphorus levels could contribute to eutrophication in receiving water bodies if discharged untreated. Overall, the collected HWW can be classified as low strength in terms of organic and SS content but characterized by elevated nutrient concentrations, particularly ammonia and phosphate.

Table 2 presents heavy metal concentrations in the collected HWW. The presence of several heavy metals in significant concentrations in the HWW indicates the complex composition of effluents generated from the Qassim University healthcare facilities. Relatively high concentrations of Fe (67 ± 1 mg L^{-1}) and Al (12 ± 0 mg L^{-1}) were detected, which are commonly associated with corrosion of plumbing systems, hospital infrastructure, and laboratory discharges. Elevated levels of Ni (1014 ± 4 µg L^{-1}), Zn (934 ± 93.5 µg L^{-1}), Cu (381 ± 38.5 µg L^{-1}), and Cr (296 ± 5.47 µg L^{-1}) were also observed, likely originating from stainless steel medical instruments, plumbing materials, and diagnostic reagents. Moderate concentrations of Mn, Mo, and V may be related to pharmaceutical residues and laboratory chemicals used in hospital activities. Additionally, potentially toxic elements such as As (1112 ± 1 µg L^{-1}), Pb (76 ± 12 µg L^{-1}), Cd (32 ± 2 µg L^{-1}), and Sb (25 ± 4 µg L^{-1}) were detected, which are of environmental concern due to their toxicity and persistence in aquatic ecosystems. The presence of these metals confirms that HWW contains diverse trace contaminants that may pose ecological risks if discharged untreated.

The relatively high standard deviations observed for several wastewater parameters indicate substantial temporal variability in the HWW characteristics. This variability can

be attributed to fluctuations in HWW composition, influenced by changes in patient numbers, medical procedures, laboratory activities, cleaning and disinfection operations, pharmaceutical use, and wastewater discharge patterns throughout the sampling period. Parameters such as COD, PO_4-P, turbidity, NH_3, Zn, and Ba varied significantly. Moreover, compared with previous studies, the relatively high concentrations of Fe, Al, As, and Ni observed in the influent HWW may be attributed to several hospital-related and site-specific factors [28]. In the present study, the elevated concentrations may be partially associated with the relatively recent establishment and ongoing expansion of Qassim University Medical City, where construction activities, the installation of new utilities, and plumbing works occurred during the study period. Consequently, metals such as Fe and Al may originate from corrosion and leaching of water distribution systems, plumbing materials, and construction-related inputs. In addition, As and Ni may be introduced through pharmaceutical residues, laboratory reagents, diagnostic chemicals, medical equipment, and cleaning products. These findings highlight the complex nature of HWW and the potential contribution of both healthcare activities and infrastructure-related sources to metal contamination. Therefore, advanced treatment technologies are needed to reduce heavy metal concentrations before wastewater discharge or reuse, minimizing potential environmental and public health risks.

3.2. Operational Performance of the LCMBR

Figure 2 shows the LCMBR operational parameters during the experimental period. Figure 2a shows that pH remained relatively stable in the slightly alkaline range (8.57 ± 0.46) throughout operation, while DO remained between approximately 6.8 and 7.7 mg L^{-1}. The stable pH suggests that biological activity and alkalinity consumption were well balanced, with no strong acidification or excessive nitrification. The consistently high DO indicates that the system was well aerated, providing favorable aerobic conditions for microbial activity and nitrification.

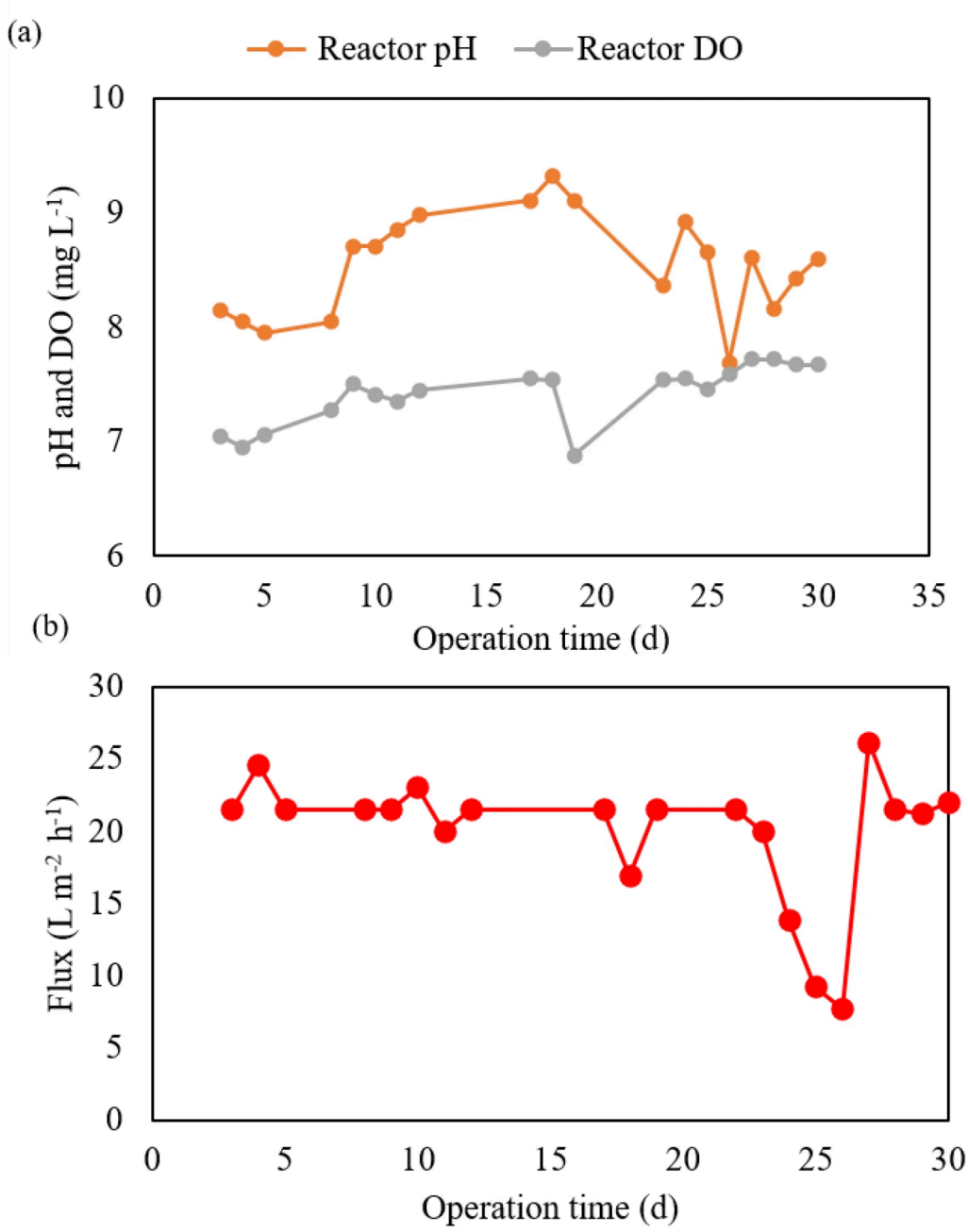

Figure 2. Operational performance of the LCMBR during the experimental period: (**a**) reactor pH and dissolved oxygen (DO), and (**b**) membrane permeate flux profile, showing a temporary decline due to membrane fouling followed by flux recovery after membrane cleaning.

To investigate membrane fouling, membrane flux was monitored, and the results are presented in Figure 2b. The permeate flux remained approximately 20–23 L m^{-2} h^{-1} during the initial operating period and subsequently declined to approximately 8 L m^{-2} h^{-1} between days 22 and 25. Following this decline, the ceramic membrane was physically cleaned using a soft brush and tap water on day 26. The permeate flux subsequently recovered to 26.2 L m^{-2} h^{-1}. This observation demonstrates that physical cleaning restored membrane permeability under the conditions of the present experiment. However, because only one cleaning event occurred during the 30-day experimental period, the results do not establish a regular membrane-cleaning interval or long-term fouling cycle. The specific fouling mechanisms cannot be identified conclusively because transmembrane pressure, membrane resistance, extracellular polymeric substances, sol-

uble microbial products, and post-cleaning membrane surface characteristics were not directly measured. Potential contributions from biomass deposition, cake-layer formation, pore blocking, and inorganic deposition therefore remain hypotheses requiring further investigation.

The LCMBR employed in this study may have further contributed to fouling mitigation. The membrane possessed a relatively large pore size (1–5 μm) and a clay-based surface, which can provide higher hydrophilicity and improved resistance to organic fouling compared with conventional polymeric membranes. The porous ceramic structure may also facilitate better permeability and reduce the formation of a dense cake layer on the membrane surface. As a result, the LCMBR maintained relatively stable flux throughout most of the operational period, with only a temporary decline associated with membrane fouling. Therefore, the LCMBR demonstrates strong potential as a cost-effective and sustainable treatment technology for HWW.

The present study did not include direct measurements of transmembrane pressure (TMP), membrane resistance, EPS, SMPs, or post-operation membrane surface characterization. Therefore, the specific fouling mechanisms responsible for the observed flux reduction cannot be conclusively identified. The stable reactor performance and consistent permeate flux observed throughout the operation suggest that severe membrane fouling was not encountered under the applied operating conditions. Based on previous MBR studies, the observed fouling may be associated with cake layer formation, pore blocking, biomass deposition, and accumulation of soluble or colloidal organic matter on the membrane surface [14]. Nevertheless, these mechanisms should be regarded as proposed explanations rather than experimentally verified phenomena. Further investigations incorporating TMP monitoring, fouling resistance analysis, EPS/SMP characterization, and membrane surface imaging are required to understand fouling behavior in the LCMBR system.

3.3. Organic Removal Performance

Removal of COD and BOD by the LCMBR during 30 d of operation is presented in Figure 3a,b. Throughout the operation, COD removal consistently exceeded 80%, and the effluent COD concentration remained below 20 mg L^{-1}, regardless of variations in influent COD. Similarly, BOD5 removal exceeded 80% (except on day 20), and effluent BOD5 was generally below 20 mg L^{-1}. The average influent and effluent COD concentrations were 139 ± 44 mg L^{-1} (n = 5) and 14 ± 6.4 mg L^{-1} (n = 10), respectively, while the average influent and effluent BOD concentrations were 57 ± 8 (n = 3) and 9 ± 6 mg L^{-1} (n = 9), respectively. These results show that the LCMBR achieved stable, efficient organic matter removal under the applied operating conditions. The consistently high COD and BOD removal efficiencies indicate that sufficient biological degradation of organic matter occurred in the reactor. The LCMBR was operated under favorable environmental conditions for microbial activity, including a pH of approximately 8.3, a DO concentration of 7.4 mg L^{-1}, and a temperature of 21 °C. These conditions fall within or near the optimal ranges reported for aerobic heterotrophic and nitrifying microorganisms [29]. The relatively high and consistently maintained DO concentration indicates that oxygen was not a limiting factor for aerobic bacterial metabolism, which is essential for achieving high COD and BOD removal rates. The system achieved high COD and BOD5 removal despite variations in influent loading (Figure 3), indicating the LCMBR's effective buffering capacity. This performance can be attributed to the long SRT of 280 d and the ceramic membranes' complete retention of biomass.

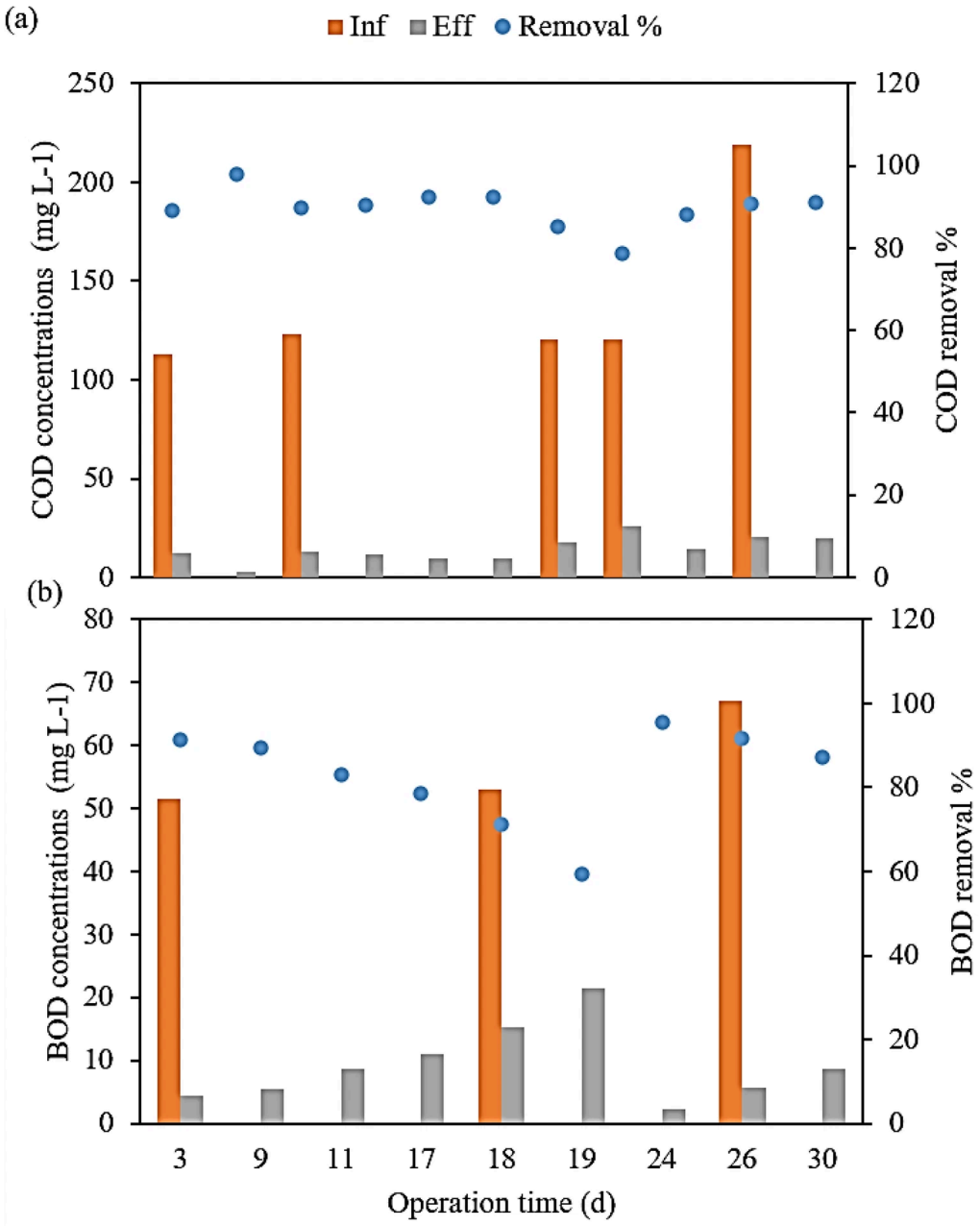

Figure 3. Influent, effluent, and % removal of (**a**) COD and (**b**) BOD in LCMBR over operation time.

The calculated F/M ratio was 0.008 g BOD g^{-1} MLSS d^{-1}, which is relatively low compared with conventional activated-sludge systems. However, this low organic loading is consistent with the MBR's long-SRT operation, in which biomass is retained in the reactor for extended periods, and a substantial fraction of the biodegradable substrate can be utilized under endogenous-respiration conditions. Previous studies have shown that low to moderate F/M ratios are associated with stable reactor operation, efficient COD removal, reduced membrane fouling, and enhanced nitrification performance [14–16]. Therefore, for the treatment of low-strength HWW, operating the LCMBR under low-to-moderate F/M conditions is an effective strategy for achieving high-quality effluent, minimizing membrane fouling, and ensuring robust performance.

3.4. Nutrient Removal Performance of LCMBR

The removal performance of inorganic nitrogen compounds (NH_3, NO_3, and NO_2)

and total inorganic nitrogen (TIN) is presented in Figure 4a–d. TIN was removed significantly throughout the operation, with approximately 50–70% removal. Among the nitrogen compounds in the HWW, NH_3-N was the dominant species, with a concentration of 50–60 mg L^{-1} (Figure 4b), whereas the effluent NH_3-N level was <1 mg L^{-1} on most operational days, except on a few days (e.g., days 17 and 19). These results indicate that ammonia was efficiently removed, primarily through biological nitrification (oxidation to NO_2 and then NO_3) and possibly partial ammonia stripping, as the pH occasionally exceeded 9.0 in the reactor (Figure 2a). Supporting this, the NO_3 profiles in Figure 4c show influent NO_3-N concentrations of 5–6 mg L^{-1} substantially increased to 10–17 mg L^{-1} in the effluent. Thus, NH_3 was oxidized to NO_3 via nitrification in the LCMBR, causing a transient increase in effluent NO_3. The low NO_2 concentrations in the effluent (Figure 4 d) indicate that NO_2 accumulation occurred only temporarily and that partial denitrification also contributed to TIN removal. The average influent TIN, NH_3-N, NO_3-N, and NO_2-N concentrations were 49 ± 11.8 mg L^{-1}, 43 ± 1, 5.3 ± 0.7, and 1.0 ± 1.4 mg L^{-1}, respectively, while the average effluent concentrations were 17 ± 2, 3.0 ± 3.5, 14.1 ± 3.2 and 0.5 ± 1.0 mg L^{-1}, respectively.

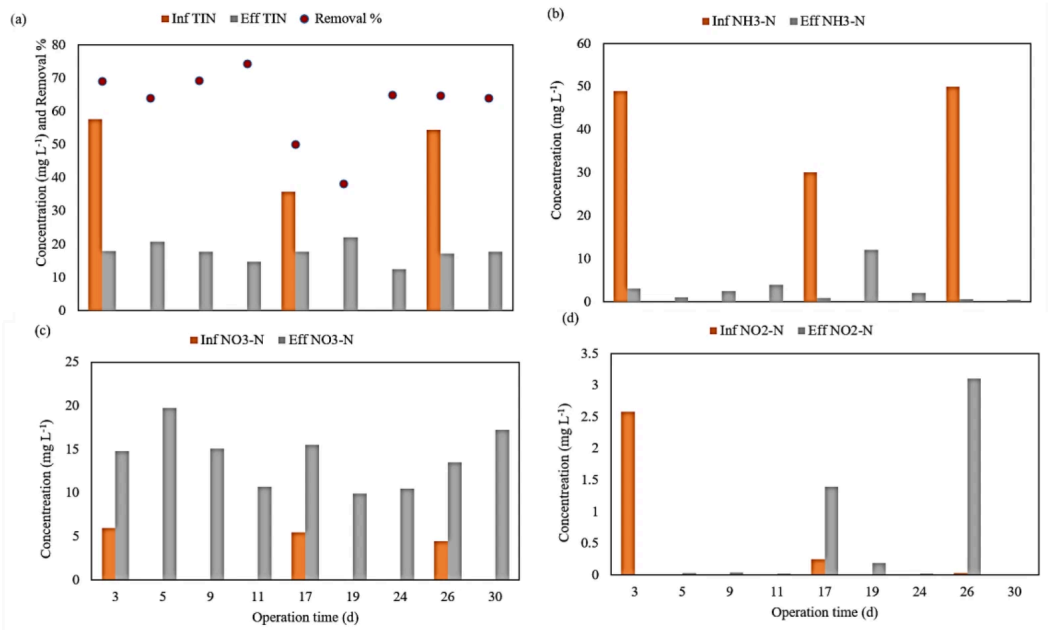

Figure 4. Variation in nitrogen removal performance of the LCMBR during the operational period: (**a**) total inorganic nitrogen (TIN), (**b**) ammonia nitrogen (NH_3-N), (**c**) nitrate nitrogen (NO_3-N), and (**d**) nitrite nitrogen (NO_2-N).

Inorganic nitrogen species in the influent and effluent (Figure 5) were calculated. Influent TIN was between 35 and 57 mg L^{-1} and was reduced to approximately 17–20 mg L^{-1} in the effluent. The substantial reduction in NH3-N, accompanied by an increase in NO3-N concentration, strongly indicates that nitrification occurred within the LCMBR system. However, nitrification alone cannot explain the observed decrease in TIN because it converts ammonia into oxidized nitrogen species rather than removing nitrogen from the aqueous phase. The reduction in TIN therefore suggests that additional nitrogen-removal or nitrogen-transfer processes may have contributed to the observed concentration changes. Possible mechanisms include denitrification within localized anoxic microenvironments inside sludge flocs or biofilms, microbial assimilation of inorganic nitrogen into biomass, and limited ammonia stripping during periods when the reactor pH exceeded 8.5. However, these mechanisms were not directly investigated in the

present study and should therefore be regarded as potential contributors to nitrogen removal rather than experimentally confirmed processes.

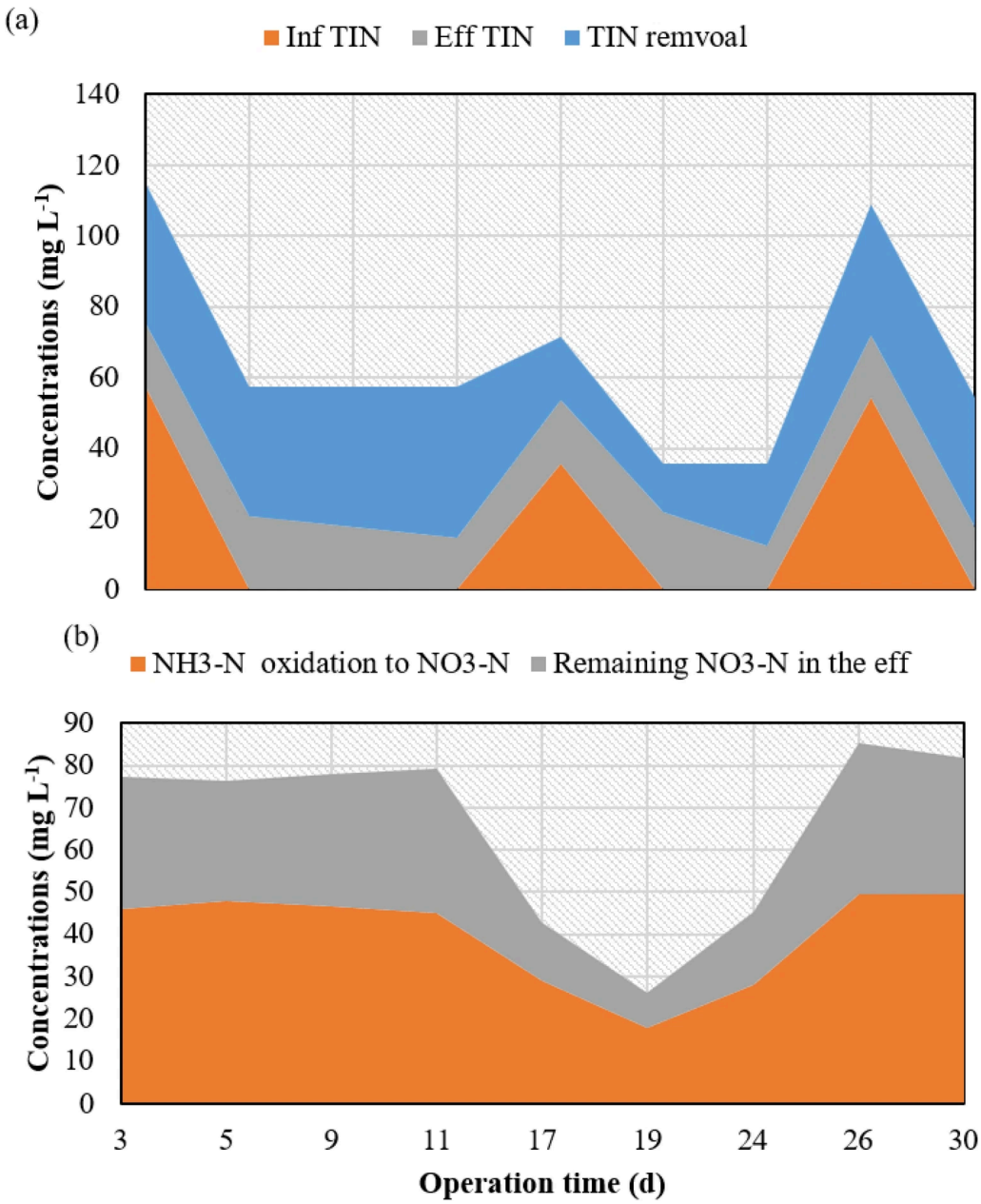

Figure 5. Comparison of influent and effluent concentrations of (**a**) total inorganic nitrogen (TIN) and (**b**) individual inorganic nitrogen species during LCMBR operation. TIN was calculated as the sum of ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_3-N), and nitrite nitrogen (NO_2-N), with all concentrations expressed as mg N L^{-1}. TIN calculations were based on corresponding sampling observations.

The present study maintained sufficient DO through continuous aeration to support NH_3 nitrification. However, even at relatively high bulk DO in the reactor, denitrification may occur due to oxygen gradients inside sludge flocs or biofilms, as well as localized DO limitations. Previous studies reported that oxygen penetration is limited by diffusion resistance and biomass density, creating internal anoxic zones where denitrification can proceed [30]. Different microbial groups localized to aerobic or anoxic regions can also facilitate simultaneous nitrification and denitrification [31]. Therefore, NH_3 was oxidized

to NO_3 in aerobic zones, while anoxic microzones created by dense flocs or biofilms reduced NO_3 to nitrogen gas (N_2). Partial TIN removal may occur through ammonium stripping as pH occasionally exceeds 9.0 [32]. Overall, TIN removal results from bulk nitrification coupled with micro-anoxic denitrification, enabling effective nitrogen removal even at high DO.

Phosphorus removal, measured as phosphate (PO_4-P), showed considerable variation in influent concentrations (9–78 mg L^{-1}) (Figure 6). During the first week of reactor operation, effluent PO_4-P concentrations increased on days 3, 4, and 5. This initial increase may be attributed to the reactor's acclimatization and stabilization phase, during which phosphorus could have been released from the seeded sludge or accumulated biomass. This release may have temporarily increased effluent phosphate concentration before the system reached more stable operating conditions. After the first week of operation, the system achieved significant PO_4 removal, with efficiencies ranging from approximately 45 to 60%. The average influent and effluent PO_4 concentrations were 44 ± 22 and 22 ± 7 mg L^{-1}, respectively. The reduction in PO_4-P concentration during the later stages of operation can be attributed to a combination of chemical precipitation and biological uptake. Occasional increases in reactor pH above 8.5 may have accelerated partial chemical precipitation of phosphorus, particularly in the presence of multivalent cations [33]. In addition, phosphorus assimilation by active biomass for cell synthesis likely contributed to the observed decrease in effluent PO_4-P concentrations [34]. Thus, P removal in the LCMBR likely results from a synergistic effect of biological uptake and pH-dependent chemical precipitation, rather than a single mechanism.

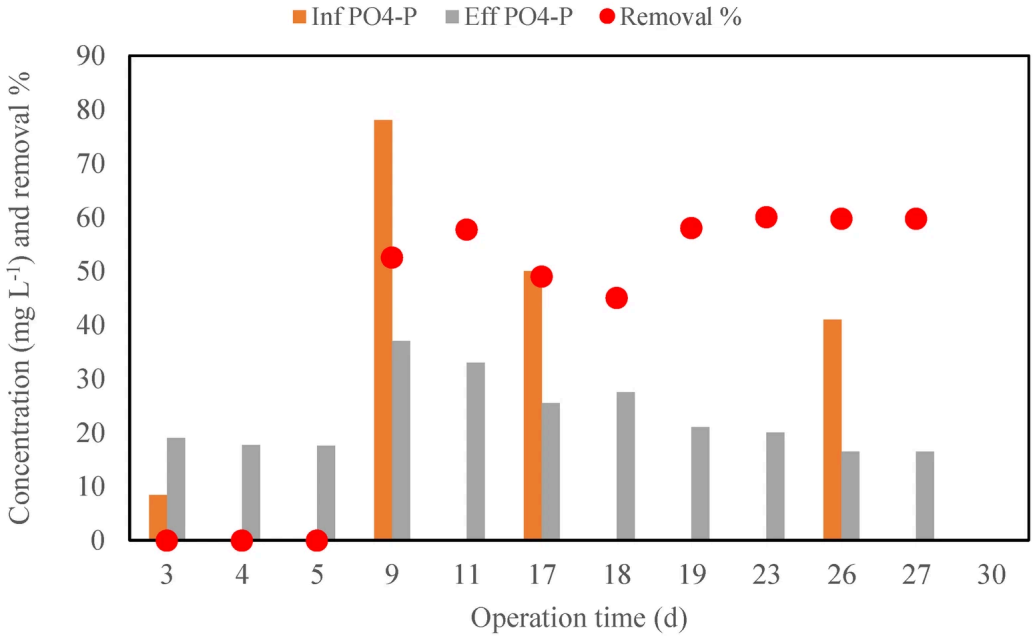

Figure 6. Influent and effluent PO_4-P concentrations and corresponding removal efficiency (%) of the LCMBR system during the 30-day operational period.

Although the LCMBR achieved moderate phosphorus removal, the treated effluent PO_4-P concentration remained above the selected guideline value for discharge or reuse in sensitive environments. Therefore, if the treated effluent is intended for discharge into nutrient-sensitive receiving waters or for reuse requiring stringent phosphorus control, an additional polishing step would likely be necessary. Potential polishing options include chemical phosphorus precipitation, adsorption using suitable sorbents, or integration of enhanced biological phosphorus removal processes. Future studies should evalu-

ate these approaches to improve phosphorus removal and broaden the applicability of the LCMBR technology.

3.5. Heavy Metal Removal by LCMBR

Figure 7 illustrates the distribution of heavy metal concentrations in the influent and treated effluent of the LCMBR system. The results clearly show that the influent HWW contained elevated concentrations of several metals, including Al, V, Cr, Mn, Fe, Co, Ni, Zn, Cu, Cd, As, Mo, Pb, Sb, and Ba. These metals are commonly found in HWW because of the extensive use of pharmaceuticals, diagnostic reagents, disinfectants, and laboratory chemicals, as well as corrosion of hospital plumbing systems [5]. The boxplots in Figure 7a–f demonstrate that metal concentrations were substantially reduced after treatment with the LCMBR system. Among the analyzed elements, Fe (67 mg L^{-1}) and Al (12.8 mg L^{-1}) showed the highest concentrations in the influent HWW. They were reduced to 1.2 and 0.03 mg L^{-1}, respectively, in the effluent (Figure 7a). Influent Cr, Zn, and Cu were found in the range of 200–400 µg L^{-1} and were reduced to 5.4, 1.7, and 38 µg L^{-1} in the effluent, respectively (Figure 7b). Concentrations of Ni, Zn, and As were found in the range of 900–1000 µg L^{-1} (Figure 7c). LCMBR reduced Ni and As to less than 5 µg L^{-1}, while Zn was reduced to 93 µg L^{-1} in the effluent (Figure 7c). V, Co, and Sb ranged from 12–25 µg L^{-1} in the influent and was reduced to less than 5 µg L^{-1} in the effluent (Figure 7d). Cd was reduced from 32 to 1.5 µg L^{-1}, and Pb was reduced from 76 to 12 µg L^{-1} (Figure 7e). Removal of Mo was efficiently reduced from 154.8 to 2.55 µg L^{-1}, whereas Ba removal was lower, decreasing from 165 to 136 µg L^{-1}.

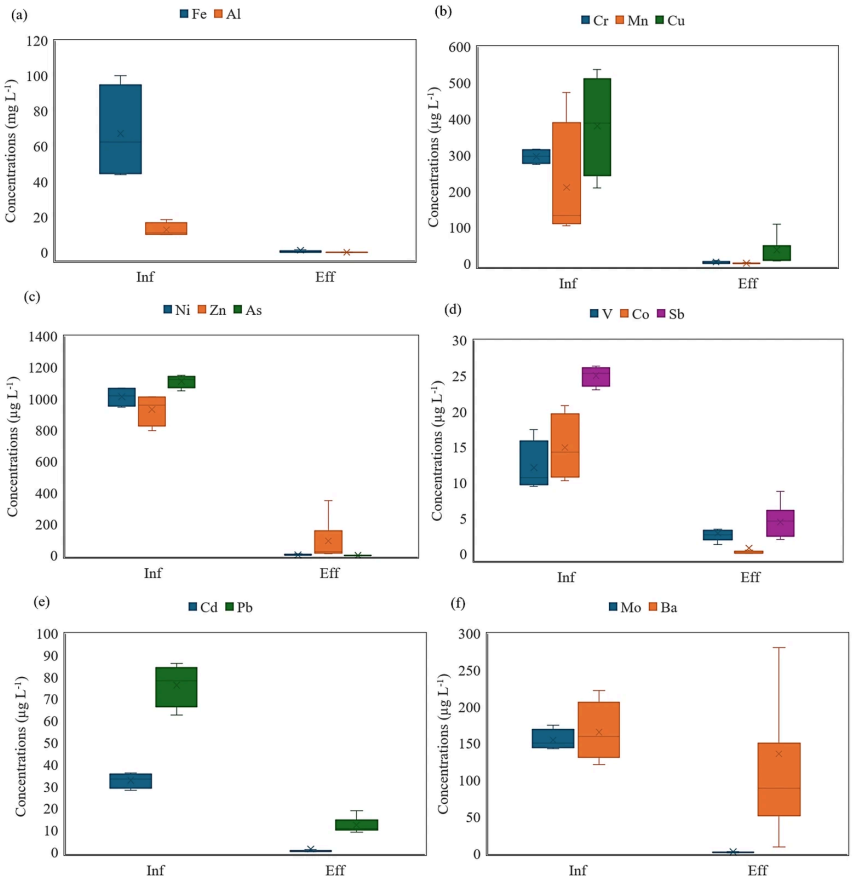

Figure 7. Box plots showing the distribution of influent and effluent concentrations of (a) Fe and Al, (b) Cr, Mn, and Cu, (c) Ni, Zn, and As, (d) V, Co, and Sb, (e) Cd and Pb, and (f)Mo and Ba in the LCMBR system treating hospital wastewater during the 30-day monitoring period.

Figure 8 presents the removal efficiencies of the analyzed metals achieved by the LCMBR system. The results indicate that the system achieved high removal efficiencies for most metals, with several elements showing removal rates exceeding 80–95%. The system achieved particularly high removal efficiencies for Al, Cr, Mn, Fe, Cu, Ni, Zn, As, Pb, Mo, Sb, and Cd. However, Ba exhibits comparatively lower removal efficiencies.

The substantial reduction in heavy metal concentrations observed in the LCMBR suggests that multiple removal processes may have contributed to the overall treatment performance. Based on previous studies, possible mechanisms include biosorption and bioaccumulation by activated sludge microorganisms, adsorption onto biomass and particulate matter, co-precipitation with metal hydroxides, and physical retention by the ceramic membrane. First, microbial biomass plays a crucial role in metal removal through biosorption and bioaccumulation processes. Microorganisms in activated sludge contain functional groups such as carboxyl, hydroxyl, and phosphate groups that can bind metal ions through ion exchange, surface complexation, and microprecipitation, facilitating their removal from wastewater [35]. Second, EPS produced by microbial communities can form complexes with metal ions, thereby enhancing their adsorption onto sludge flocs. EPS contain abundant functional groups such as carboxyl, hydroxyl, and amino groups, which provide binding sites for metal ions through mechanisms including electrostatic interaction, ion exchange, and complexation. In addition, the extended SRT maintained in LCMBR systems promotes the enrichment of specialized microbial populations capable of tolerating and immobilizing metal ions within the biomass matrix [36].

Another potential mechanism contributing to metal immobilization in the LCMBR is the relatively high iron concentration in the hospital wastewater. In the present study, the measured influent iron concentration was approximately 67 mg L^{-1} following acid digestion. Therefore, this value represents digestion-recovered iron rather than specifically dissolved iron. Under the aerobic conditions of the LCMBR, any dissolved ferrous iron (Fe^{2+}) in the wastewater could oxidize to ferric iron (Fe^{3+}), potentially forming hydrous ferric oxide (HFO) precipitates. These iron hydroxides are characterized by reactive surface hydroxyl groups that can provide adsorption sites for dissolved metal ions. Consequently, surface complexation, adsorption, and co-precipitation with iron hydroxide precipitates may help immobilize metals such as Cu, Cd, and Pb. Previous studies have shown HFO's strong affinity for these metals, primarily through surface complexation and adsorption [37]. Nevertheless, the formation and contribution of HFO to metal removal were not directly verified in the present study through iron speciation or solid-phase characterization. Thus, iron-mediated metal immobilization is considered a plausible contributing mechanism rather than an experimentally confirmed removal pathway.

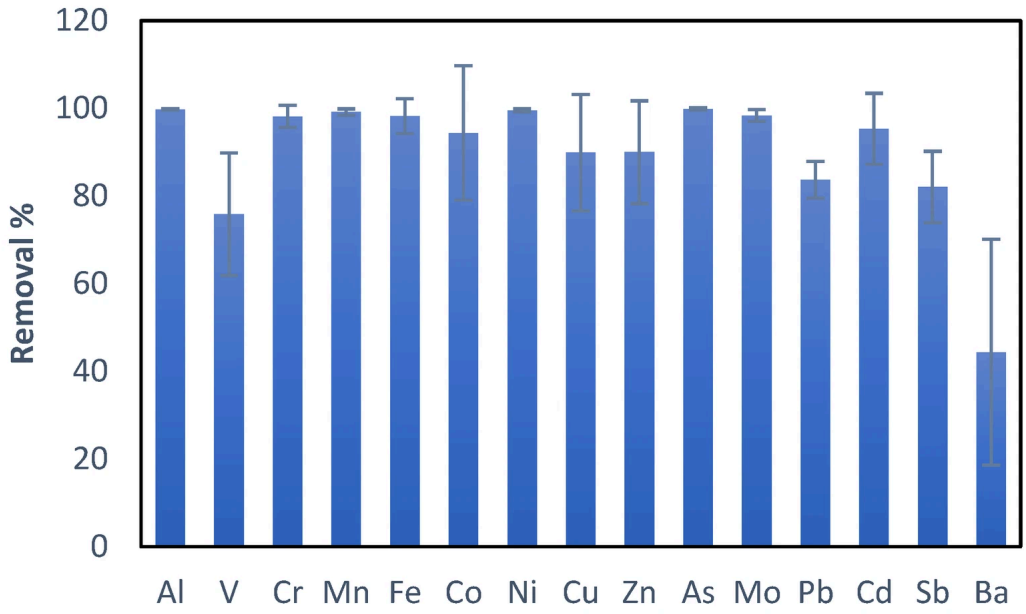

Figure 8. Removal efficiencies (%) of heavy metals in the LCMBR treating hospital wastewater. Error bars represent the standard deviations (SDs) of the removal efficiencies calculated from 14 effluent wastewater samples (n = 14).

The LCMBR treatment mechanisms involved complementary biological, physicochemical, and physical separation processes. Given its nominal pore size of 1–5 μm, the ceramic membrane primarily functions as a microfiltration barrier, retaining suspended biomass, suspended solids, and particulate or colloidal matter. Heavy metals associated with sludge flocs, extracellular polymeric substances (EPSs), and iron (hydr)oxide precipitates may consequently be retained within the bioreactor through membrane filtration. However, dissolved metal ions may pass through the microfiltration membrane, and their removal depends primarily on physicochemical interactions and transformations occurring within the bioreactor, including potential adsorption, biosorption, precipitation, and co-precipitation. Therefore, the observed reductions in aqueous-phase metal concentrations may reflect the transfer of metals from the liquid phase to biomass, sludge, iron (hydr)oxide precipitates, and other retained solids rather than their complete elimination from the treatment system. Appropriate sludge handling and management are therefore essential considerations for the practical implementation of LCMBR technology.

3.6. Treatment Potential and Practical Implications of LCMBR

HWW contains a complex mixture of organic pollutants, nutrients, pharmaceuticals, disinfectants, and heavy metals, making its treatment more challenging than conventional municipal wastewater [2,11]. In this study, the LCMBR effectively removed organic matter and nutrients, confirming its potential as a decentralized treatment technology for healthcare facilities. Treating HWW with an LCMBR offers an economical alternative to conventional MBR systems that rely on expensive commercial polymeric membranes. The treated effluent demonstrated compliance with the selected guideline values for COD, BOD_5, SS, inorganic nitrogen species, and the measured trace metals under the wastewater discharge and irrigation reuse scenarios evaluated in this study (Table 3). The effluent COD (14 mg L^{-1}) and BOD (9 mg L^{-1}) were well below the recommended limits for both irrigation reuse and surface water discharge, as established by the World Health Organization (WHO) [38] and the United States Environmental Protection

Agency (USEPA) [39]. Nitrogen species in the treated effluent were also within acceptable ranges. The concentrations of NH_3-N (2.94 mg L^{-1}), NO_2-N (0.6 mg L^{-1}), and NO_3-N (14 mg L^{-1}) fall within safe limits for agricultural irrigation. However, PO_4-P (22 mg L^{-1}) exceeded the most conservative thresholds recommended for nutrient-sensitive receiving waters and certain crops, indicating that additional phosphorus control may be necessary before reuse in sensitive environments. Similarly, the measured trace-metal concentrations were below the corresponding guideline values considered in this study.

Table 3. Comparison of organics, nutrients, and heavy metal concentrations in LCMB effluent with WHO/FAO irrigation guidelines [38] and USEPA discharge standards [39].

Parameters	LCMBR Effluent	WHO/FAO Irrigation Guideline	USEPA Discharge Guideline	Compliance
Organics and nutrients				
COD (mg L^{-1})	14	<100	120	Safe
BOD (mg L^{-1})	9	<50	30	Safe
NH_3–N (mg L^{-1})	2.94	-	1.0–3.0	Safe
NO_3–N (mg L^{-1})	14.8	10–50	-	Safe
NO_2–N (mg L^{-1})	0.6	<1	<1	Safe
PO_4–P (mg L^{-1})	22.8	10	-	Exceeded
Heavy metals				
Al (mg L^{-1})	0.032	5	–	Safe
Cr (mg L^{-1})	0.005	0.1	0.5	Safe
Mn (mg L^{-1})	0.0018	0.2	–	Safe
Fe (mg L^{-1})	1.2	5	–	Safe
Ni (mg L^{-1})	0.0045	0.2	–	Safe
Cu (mg L^{-1})	0.039	0.2	1.0	Safe
Zn (mg L^{-1})	0.094	2	2.0	Safe
As (mg L^{-1})	0.0015	0.1	0.1	Safe
Mo (mg L^{-1})	0.0026	0.01	–	Safe
Pb (mg L^{-1})	0.012	5	0.5	Safe
Cd (mg L^{-1})	0.0015	0.01	0.01	Safe
Sb (mg L^{-1})	0.0045	–	–	–
Ba (mg L^{-1})	0.13	–	2	Safe
V (mg L^{-1})	0.003	0.1	0.1	Safe
Co (mg L^{-1})	0.0001	0.05	0.05	Safe

The treated effluent concentrations were compared with selected reference values from international wastewater reuse and discharge guidance documents. These comparisons indicate the LCMBR's relative treatment performance for the measured parameters; however, they do not establish universal compliance with all wastewater discharge or reuse requirements. The applicability of individual guideline values depends on the intended reuse or discharge category, the receiving environment, and the relevant regulatory framework. In particular, the present study did not assess microbiological quality, pharmaceuticals, antibiotic-resistant microorganisms, or antibiotic-resistance indicators. Consequently, the treated effluent cannot be declared safe for unrestricted agricultural irrigation, environmental discharge, or other reuse applications based solely on the mea-

sured physicochemical parameters and trace metals.

From a practical perspective, the LCMBR represents a potentially affordable treatment option for decentralized hospital wastewater management, particularly in resource-constrained settings. The cost and energy assessment presented in Table 4 combines experimentally measured operating parameters with preliminary engineering estimates for a hypothetical decentralized hospital wastewater treatment facility with a design capacity of 10 m^3 d^{-1}. The experimentally determined parameters included the membrane surface area (0.04 m^2), average permeate flux (approximately 20 L m^{-2} h^{-1}), aeration rate (9.6 ± 2.7 L min^{-1}), and operating conditions observed during the 30-day experimental period. Based on the experimentally observed average permeate flux and an assumed continuous operating period of 24 h d^{-1}, approximately 21 m^2 of membrane area would be required to treat 10 m^3 of wastewater daily.

Table 4. Operational, economic, and energy parameters of the low-cost ceramic membrane bioreactor (LCMBR) for small community hospital wastewater treatment.

Parameter	Estimation	Notes/Additional Info
Total wastewater production	10 m^3 d^{-1}	Average daily flow from a small community hospital
Membrane area needed	21 m^2	Calculated based on a flux 20 L m^{-2} h^{-1}
Membrane cost	105 US$ (5 US$ m^{-2})	Low-cost ceramic membranes can be reused for multiple years
Energy consumption (kWh m^{-3})		
Feed pump	0.030	Feeding raw wastewater into the bioreactor
Permeate pump	0.050	Draws treated water through a membrane
Aeration pump	0.050	Provides continuous oxygen and scours membranes
Backwashing	0.0028	Occurs every 20 days; minimal contribution, if mechanical backwashing was used.
Total energy consumption	0.133	Very low compared to conventional MBRs (0.5–1.0 kWh m^{-3})
Membrane cleaning frequency	0.05 d^{-1}	Low biomass operation reduces fouling rates
Expected membrane lifetime	4–5 yr	Depends on water quality and cleaning regimen
O&M	Simple	Suitable for small-scale, low-resource hospitals

The energy assessment represents a preliminary engineering estimation rather than a direct measurement of electricity consumption during the laboratory-scale experiment. Energy requirements for feed pumping, permeate pumping, aeration, and periodic mechanical cleaning/backwashing were estimated using the calculation procedure de-

scribed by Shafiquzzaman et al. [18], based on the design flow rate and the engineering assumptions summarized in Table 4. The estimated energy contributions were approximately 0.030 kWh m^{-3} for feed pumping, 0.050 kWh m^{-3} for permeate pumping, 0.050 kWh m^{-3} for aeration, and 0.0028 kWh m^{-3} for mechanical cleaning/backwashing. The latter contribution was calculated assuming a backwashing frequency of once every 20 days. Accordingly, the total estimated specific energy requirement was approximately 0.133 kWh m^{-3}. Compared with the reported energy consumption of conventional membrane bioreactors (0.4–1.15 kWh m^{-3}) [40], this preliminary estimate indicates the potential for lower operational energy requirements. Nevertheless, interpret this comparison cautiously, as the estimate is based on specific engineering assumptions and has not been validated through electricity consumption measurements in a pilot- or full-scale LCMBR installation.

Regarding membrane costs, the estimated fabrication cost of US$0.2–0.3 per unit reflects material and manufacturing costs under laboratory-scale conditions. For the hypothetical 10 m^3 d^{-1} facility, the estimated membrane requirement of approximately 21 m^2 corresponds to a total membrane cost of approximately US$105, based on an assumed membrane cost of US$5 m^{-2} [19]. This relatively low estimated cost may provide an economic advantage over conventional commercial polymeric membranes and potentially reduce the initial membrane-related capital investment in small-scale treatment facilities. However, the assumed membrane lifetime of 4–5 years represents a preliminary design assumption rather than an experimentally established service life, as the present investigation covered only 30 days of operation. Actual membrane durability will depend on operating conditions, cleaning procedures, mechanical integrity, and long-term permeability recovery. Furthermore, the laboratory experiment used manual brushing with tap water as the cleaning procedure; mechanical backwashing was not experimentally investigated. Therefore, the backwashing-related energy contribution included in Table 4 represents a separate engineering assumption for the hypothetical treatment facility rather than an experimentally validated operating requirement.

Overall, the preliminary cost and energy assessment suggests that the LCMBR has potential economic advantages for decentralized hospital wastewater treatment. However, the estimated energy demand, membrane replacement period, and associated costs require validation through long-term pilot- or full-scale operation. Future techno-economic assessments should incorporate sensitivity analyses addressing membrane lifetime, cleaning frequency, aeration requirements, pumping energy, and other operational and maintenance expenditures to establish the long-term economic feasibility and practical scalability of the proposed system.

These features collectively make the LCMBR particularly suitable for decentralized HWW treatment in small healthcare facilities. In many developing countries, including those in the Middle East and South Asia, small hospitals, primary healthcare centers, and private clinics often lack dedicated on-site wastewater treatment systems [9]. Consequently, hospital effluents are frequently discharged directly into municipal sewer networks or nearby drainage systems without adequate treatment, increasing the risk of environmental contamination and the spread of antibiotic-resistant microorganisms. Compact, low-cost treatment technologies that can operate with minimal technical expertise are therefore essential to improve HWW management in such settings [41]. In KSA, the healthcare sector has expanded rapidly in recent years due to population growth and increasing demand for medical services. Alongside large tertiary hospitals, numerous small healthcare facilities, including primary health care centers, private clinics, and rural hospitals, serve local communities nationwide. Many of these facilities generate relatively small volumes of wastewater, typically 10–15 m^3 d^{-1}. However, the

wastewater may still contain pharmaceuticals, disinfectants, nutrients, and trace metals that require proper treatment before discharge or reuse. Installing large, centralized treatment systems in these facilities is often impractical because of limited space, operational complexity, and high capital costs.

In this context, decentralized treatment systems based on LCMBR technology offer several practical advantages. The compact footprint, robust operation, and relatively low sludge production make LCMBR systems well-suited for on-site treatment in small healthcare facilities. In addition, LCMBR has considerable potential for producing high-quality treated wastewater for non-potable reuse applications, such as landscape irrigation, particularly in water-scarce regions such as Saudi Arabia [41]. However, the suitability of LCMBR-treated hospital wastewater for specific reuse applications requires further assessment, including microbiological quality and compliance with the relevant reuse standards. Decentralized LCMBR systems could therefore support sustainable water management strategies by enabling safe wastewater reuse while reducing the pollutant load discharged into municipal sewer networks or the environment. Overall, integrating LCMBR technology into decentralized wastewater treatment systems could provide an effective, economically viable solution for managing HWW in small healthcare facilities in developing countries. In arid regions such as Saudi Arabia, where water resources are limited and wastewater reuse is increasingly encouraged, these technologies have significant potential to enhance environmental protection while supporting sustainable water reuse practices.

4. Limitation and Future Study

The treatment performance observed in this study resulted from the combined effects of biological treatment within the reactor and physical separation by the ceramic membrane under the applied hydraulic and aeration conditions. Several operational and wastewater characteristics, including the relatively long solids retention time (SRT), high initial biomass concentration, low organic loading rate, and elevated iron and aluminum concentrations in the wastewater, may have contributed to the observed treatment performance. However, because the experimental design did not include a matched conventional polymeric MBR, activated-sludge-only control, or membrane-only control, the individual contribution of the ceramic membrane material to the overall treatment efficiency cannot be independently quantified. Furthermore, the relatively short experimental period (30 days) and a single membrane-cleaning event provide preliminary evidence of laboratory-scale operational feasibility but are insufficient to establish long-term membrane durability, sustained fouling resistance, or the technology's broader applicability across different healthcare facilities. Future comparative investigations should therefore evaluate the LCMBR against conventional polymeric MBR and conventional activated-sludge configurations under equivalent operating conditions to distinguish the contributions of biological treatment, membrane filtration, and membrane material properties.

Further operational optimization is also needed to improve the LCMBR's energy efficiency and nutrient-removal performance. In particular, intermittent aeration strategies should be investigated to reduce energy consumption while maintaining adequate dissolved oxygen concentrations, effective biomass suspension, and membrane scouring, as aeration generally accounts for a major share of MBR energy demand. In addition, phosphorus removal requires further improvement, potentially through chemical precipitation or integration with other nutrient-removal processes. Future investigations should also examine the removal of pharmaceutical micropollutants and other emerging contaminants commonly detected in hospital wastewater, as their presence may pose addi-

tional environmental risks even when conventional water-quality parameters are effectively reduced. Long-term pilot-scale investigations incorporating membrane fouling characterization, cleaning optimization, energy monitoring, and comprehensive techno-economic assessment are therefore essential to establish the operational reliability, sustainability, and practical applicability of LCMBR technology for decentralized hospital wastewater treatment.

5. Conclusions

This study assessed the treatment performance of an LCMBR for HWW treatment. The LCMBR system effectively treated HWW while maintaining a relatively stable MLSS concentration, a low F/M ratio of 0.008 g BOD g^{-1} MLSS d^{-1}, and a stable permeate flux of 20 L m^{-2} h^{-1}, with low membrane fouling rates (one per 23 days) throughout operation. The LCMBR achieved high removal efficiencies for organic pollutants, inorganic nitrogen species, and trace metals. Significant reductions in COD (average removal efficiency of 90%) and BOD_5 (average removal efficiency of 83%) were achieved through the combined effects of biological degradation and membrane filtration. Nitrogen transformation occurred primarily through nitrification, resulting in low ammonia and nitrite concentrations in the treated effluent. Phosphorus removal was moderate and was primarily attributed to biological uptake and adsorption onto biomass. The system also demonstrated effective heavy-metal removal, with efficiencies ranging from 44% to 99%. Furthermore, the concentrations of all 15 investigated trace metals in the treated effluent were below the applicable international discharge and irrigation guideline limits established by the WHO and USEPA. A key advantage of the proposed system is the use of locally fabricated ceramic membranes, which significantly reduce capital costs compared with commercial polymeric membranes while maintaining good operational stability and fouling resistance. The total energy consumption of the LCMBR was estimated at 0.132 kWh m^{-3}, with the aeration and permeate pumps being the main contributors, and backwashing contributing minimally (0.0028 kWh m^{-3}). This low energy requirement further highlights the system's suitability for small, decentralized hospitals and other low-resource settings. The simplicity and cost-effectiveness of the LCMBR make it particularly suitable for decentralized wastewater treatment applications in small hospitals, rural clinics, and developing regions.

The findings of this study are limited to a laboratory-scale system operated for 30 days. The system's performance in pathogen and pharmaceutical/micropollutant removal, long-term membrane durability, and sludge-associated metal accumulation was not investigated. Furthermore, phosphorus removal remained limited, as the effluent PO_4-P concentrations exceeded the selected guideline value, highlighting the need for additional phosphorus removal measures to improve the suitability of the treated effluent for potential reuse applications. Detailed fouling characterization, including TMP monitoring, membrane resistance analysis, EPS/SMP quantification, and membrane surface characterization, was beyond the scope of this work. Future studies should incorporate these analyses to identify dominant fouling mechanisms and optimize long-term membrane performance. Therefore, while the LCMBR represents a promising treatment approach for decentralized HWW management, further research is required before full-scale implementation can be recommended. Future studies should focus on long-term pilot-scale testing under real operating conditions, optimization of phosphorus removal, monitoring of pathogens and emerging contaminants, evaluation of sludge-metal management strategies, assessment of membrane fouling and durability, and comprehensive energy and cost analyses to support practical application and technology scale-up. With further optimization, LCMBR technology could provide a sustainable, cost-effective so-

lution for HWW management.

Author Contributions: F.A.A.: Methodology, Investigation, Formal analysis, Writing—original draft. M.S.: Conceptualization, Methodology, Investigation, Formal analysis, Supervision, Funding acquisition, Writing—original draft. M.J.: Investigation, Writing—review & editing. M.A.: Validation, Writing—review & editing. A.E.A.E.A.: Formal analysis, Writing—review & editing. S.A.A.: Writing—review & editing. A.S.A.: Writing—review & editing. A.T.A.: Writing—review & editing. H.H.: Conceptualization, Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

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