

Full-Scale Evaluation of a Hospital Wastewater Treatment Plant Upgrade: Retrofit from Extended Aeration to Moving Bed Biofilm Reactor Technology

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ARTICLE INFO

RESEARCH PAPER

Article history:
Received:
 January 2026
Revised:
 February 2026
Accepted:
 May 2026

Keywords:
 Hospital wastewater;
 Moving bed biofilm reactor (MBBR);
 Extended aeration;
 Kinetic modelling;
 Multi-criteria assessment;
 Sludge reduction.

Abstract:

This study presents a full-scale before–after evaluation of upgrading the Nikan Hospital (Tehran, Iran) wastewater treatment plant from an Extended Aeration (EA) activated-sludge process to a Moving Bed Biofilm Reactor (MBBR) by retrofitting the existing aeration tank with Kaldnes K3 carriers (40% fill) and introducing upstream screening/equalization and an anoxic zone. Over a six-month monitoring program (3 months under EA and 3 months under MBBR; composite sampling three times per week), conventional performance indicators (COD, BOD₅, NH₄⁺-N, TN, TP, and TSS) were measured and compared statistically. The results showed that the retrofit produced higher and more stable removals after start-up stabilization: COD and BOD₅ > 90%, NH₄⁺-N 70–85%, TN 65–75%, and TP 50–60%, with effluent TSS of 25–30 mg/L. Excess sludge yield decreased by 75% (0.50–0.60 to 0.12–0.15 kg VSS kg⁻¹ COD removed), lowering sludge handling frequency and contributing to an overall OPEX reduction of 35–40%. Specific aeration energy increased modestly (from 0.74 to 0.83 kWh m⁻³) due to carrier-mixing requirements, but energy intensity per kg COD removed decreased slightly because of improved removal. A first-order CSTR kinetic model was calculated from the full-scale data and was applied to estimate apparent rate constants and the HRT required to meet target effluent concentrations, supporting the observed capacity gain (effective HRT from 24 h to 9 h) within the same footprint.

1. Introduction

Conventional biological wastewater treatment processes face several inherent limitations when applied to hospital WWTPs. Hospital effluents are particularly challenging because they may contain a broad spectrum of pharmaceuticals, disinfectants, and pathogenic microorganisms that are not fully addressed by conventional secondary treatment [1-2]. Hospital effluent is typically characterized by fluctuating hydraulic and organic loads, high nutrient concentrations, and the presence of pathogens and pharmaceutical residues that are difficult to biodegrade. These characteristics and associated environmental risks have been widely documented for hospital effluents [3-5,38].

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From a sustainability perspective, recent assessments emphasized the need for energy- and resource-efficient hospital wastewater treatment strategies [6]. Recent reviews further identify hospital wastewater as a hotspot for pathogenic microorganisms and antimicrobial resistance dissemination [7]. Among traditional biological systems, the Activated Sludge Process (ASP) and its variants—particularly the Extended Aeration (EA) configuration—are the most widely adopted because of their operational simplicity and established performance in organic matter removal. However, these systems are constrained by high energy demand (typically 0.7–0.9 kWh m⁻³), large sludge yields (0.5–0.6 kg VSS kg⁻¹ COD removed), and long hydraulic retention times (HRTs), often exceeding 20 h, which make them less suitable for space-limited hospital sites [8-11].

Alternative suspended-growth and hybrid systems have been implemented to overcome these constraints. Sequencing Batch Reactors (SBRs) offer flexible operation and compact design but it requires precise cycle control and continuous operator attention, making them vulnerable to process upsets [10]. Oxidation Ditches (ODs) provide robustness against load fluctuations but occupy large areas and entail long HRTs. Trickling Filters (TFs) and Aerated Lagoons (ALs), though energy-efficient, are seldom used in modern hospital applications due to clogging, odor generation, and limited nutrient removal efficiency [9-10]. The tightening of discharge standards and escalating energy costs intensify the demand for compact, energy-efficient, and resilient treatment technologies. In dense urban areas, upgrading existing wastewater treatment plants is often preferable to expanding plant footprints, particularly for hospital facilities where uninterrupted operation is required. This shift is reinforced by energy-benchmarking studies, showing that aeration typically dominates electricity use in conventional activated-sludge configurations [11]. Among biofilm-oriented processes, the Moving Bed Biofilm Reactor (MBBR) has gained wide adoption since its development in Norway in the late 1980s, owing to its compact footprint, high volumetric loading capacity, and operational robustness [12,13]. Subsequent pilot- and full-scale applications have confirmed these advantages in practice [14-16]. Moving-bed biofilm studies have demonstrated effective nitrification and nitrogen removal under variable loading [17,18], and related research on simultaneous nitrification–denitrification highlights the importance of hydraulics and process configuration for nitrogen removal [33]. Design and operation have been refined through oxygen-transfer and carrier-performance considerations as well as mechanistic modelling approaches [19,20,24]. Staged nitrifying/denitrifying MBBR configurations have also demonstrated biodegradation of selected pharmaceuticals in hospital wastewater [21,22], although post-treatment and disinfection are often still required to address pathogens and persistent micropollutants. Beyond municipal and hospital contexts, MBBR has been applied to challenging industrial effluents (e.g., formaldehyde and petroleum wastewater) [31,32], and numerical optimisation tools such as response surface methodology have been used to quantify process sensitivity and guide design [34]. In addition, integrated fixed-film activated sludge (IFAS) and other hybrid attached-growth systems build on similar carrier-based principles; their design and optimisation are increasingly supported by pilot studies, process modelling and nitrification safety-factor concepts [23-25]. More broadly, numerical optimisation of environmental parameters for biological pollutant removal has been applied across wastewater contexts [36].

The present study addresses this knowledge gap by conducting a full-scale comparative evaluation of a 200-bed hospital WWTP in Tehran before and after its conversion from EA to MBBR technology. The work quantifies changes in (i) organic matter removal (COD, BOD₅), (ii) nutrient removal (NH₄⁺-N, TN, TP), (iii) sludge production, (iv) energy use, and (v) operational costs and footprint. In addition to conventional performance reporting, the study introduces a quantitative assessment layer through (a) statistical testing of before–after differences and (b) back-calculation of an apparent first-order kinetic model that enables performance projection at alternative HRTs. Accordingly, the central hypothesis tested is that MBBR retrofitting can enhance effluent quality and operational efficiency while reducing overall costs and sludge generation within an unchanged physical footprint. Because the routine monitoring program at the site focused on conventional parameters, direct measurements of pharmaceuticals and pathogens were beyond the scope of this work; this limitation is explicitly stated and used to frame the discussion and recommendations for future research.

2. Materials and Methods

2.1 Site Description


Nikan Hospital, located in northern Tehran, Iran, is a 200-bed private healthcare complex that generates substantial wastewater from its medical, diagnostic, and support activities. The average wastewater generation rate was estimated at 1,000 L bed⁻¹ day⁻¹, yielding a design flow of approximately 200 m³ day⁻¹. The hospital originally operated a conventional EA system for biological treatment. Although the EA configuration initially provided stable operation, several performance challenges emerged as the facility expanded. The commissioning of a new laundry unit and higher patient occupancy led to hydraulic shock loads, biomass washout, and recurrent clogging of the lamella settlers in the secondary clarifier. Consequently, treatment reliability declined and effluent quality became inconsistent. To resolve these limitations, the WWTP was retrofitted to a MBBR process. The upgraded layout incorporated (i) coarse and fine screening, (ii) an equalization tank for flow and load homogenization, and (iii) an anoxic zone upstream of the aeration basin to enhance nitrogen removal. The problematic lamella settlers were dismantled to prevent recurring blockages and simplify operation. Regarding sludge management, the hospital had previously used a screw-press dewatering unit. However, high disposal costs and the hazardous characteristics of hospital sludge—containing infectious materials and trace heavy metals—rendered this option unsustainable. The revised management strategy therefore emphasized sludge-minimizing biological operation combined with off-site disposal through licensed contractors.

In summary, the transition from EA to MBBR at Nikan Hospital was motivated by operational instability, limited available space, and the need for higher treatment resilience. The upgraded configuration aimed to ensure consistent effluent compliance, reduce excess-sludge generation, and enhance adaptability to the variable composition of hospital wastewater.

2.2 MBBR Upgrade Design and Implementation

The retrofit of the Nikan Hospital WWTP from Extended Aeration (EA) to a MBBR configuration was designed based on practical, site-specific constraints to maximize reuse of the existing infrastructure. The selected carrier medium was Kaldnes K3 (manufactured in Belgium and commercially available in Iran), offering an effective specific surface area of approximately $500 \text{ m}^2 \text{ m}^{-3}$ and neutral buoyancy, making it suitable for high-strength hospital wastewater. A carrier filling fraction of 40 % of the aeration tank volume was adopted to ensure sufficient biofilm growth and process stability, while maintaining uniform hydraulic performance. The key characteristics of the selected carrier media are summarized in Table 1.

Table 1: Characteristics of carrier media used in the MBBR system

Item	Characteristics
Model	Kaldnes K3
Geometry	 Cylindrical carrier with internal cross-ribs (K3 type)
Material	High-density Polyethylene (HDPE)
Density	950 kg/m^3
Thickness	1.8 mm
Diameter	16 mm
Porosity	85%
Effective surface area	approximately $500 \text{ m}^2/\text{m}^3$
Country of manufacture	Belgium

The aeration system and fine-bubble diffusers from the original EA configuration were retained, as their capacity was sufficient to maintain dissolved oxygen (DO) levels of $2.5\text{--}3.0 \text{ mg L}^{-1}$ and ensure effective carrier circulation. Only minor positional adjustments were made to the diffusers to promote uniform carrier distribution and minimize dead zones. To prevent media washout, a stainless-steel screening basket (Fig. 1) was installed at the aeration-basin outlet. Additionally, the lamella settlers—which had been prone to clogging and frequent maintenance under EA operation—were completely removed, improving hydraulic stability and long-term operational reliability.



Fig. 1: Trap/screening baskets at the outlet of the aeration basin to prevent carrier washout

The implementation was completed in two phases over a two-week period:

- **Phase 1 (Week 1):** Removal of lamella settlers, installation of the media trap, and preparation of the aeration basin.
- **Phase 2 (Week 2):** Introduction of Kaldnes K3 media, operational checks of aeration, and gradual ramp-up of loading until effluent quality stabilized.

Key design considerations included compatibility with existing infrastructure, cost-effectiveness, minimal downtime for hospital operations, and regulatory compliance. Overall, the retrofit demonstrated the advantages of MBBR as a compact, low-maintenance, and operationally robust technology for hospital wastewater treatment.

Comparison of EA and MBBR design aspects is summarized in Table 2.

Table 2: Comparative summary of EA vs. MBBR retrofit design aspects.

Design Aspect	Extended Aeration (EA)	Retrofit with MBBR
Carrier Media	N/A	Kaldnes K3 media
Aeration System	Fine-bubble diffusers (existing) for O_2 supply/mixing	Same fine-bubble diffusers retained, no modification
Tank Configuration	Aeration basin + lamella clarifier (prone to clogging)	Existing basin reused; lamella removed; trap/screen installed
Implementation Phases	Original installation only	Two-week retrofit: 1 week modification + 1 week media installation
Design Considerations	Large footprint; clogging issues; high operational loads	Compact footprint; robust performance; compatible with infrastructure

2.3 Performance Monitoring and Evaluation Parameters

To assess the effectiveness of upgrading the Nikan Hospital WWTP from an Extended Aeration (EA) system to a Moving Bed Biofilm Reactor (MBBR), a monitoring program was implemented to track influent/effluent quality, process performance, and operational indicators. Key conventional water-quality parameters were measured in accordance with Standard Methods [26] to evaluate

treatment efficiency and regulatory compliance. The monitored parameters included:

- Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD₅) — indicators of biodegradable organic load removal;
- Total Suspended Solids (TSS) — representing particulate removal and clarification performance;
- Ammonium nitrogen (NH₄⁺-N), Total Nitrogen (TN) and Total Phosphorus (TP) — used to assess nutrient removal and nitrification/denitrification performance.

Operational metrics included dissolved oxygen (DO), hydraulic retention time (HRT), specific aeration energy (kWh m⁻³) and energy intensity per kg COD removed (kWh kg⁻¹ COD removed), as well as excess sludge yield (kg VSS kg⁻¹ COD removed). These metrics provide an integrated basis for comparing the suspended-growth EA baseline and the attached-growth MBBR retrofit. Direct measurements of pharmaceuticals and pathogens were not part of the routine monitoring program and are addressed as a limitation in the Discussion.

2.4 Data Collection and Analysis Techniques

A rigorous monitoring framework was established to ensure the accuracy, consistency, and reproducibility of the performance comparison between the EA and MBBR systems. The six-month campaign was divided into two equal monitoring periods: 12 weeks of baseline EA operation immediately before the retrofit, followed by 12 weeks of MBBR operation after media installation (including the start-up stabilization discussed in Section 3.6). Wastewater samples were collected three times per week from both influent and effluent points to capture temporal variability. Twenty-four-hour flow-proportional composite samples were used for COD, BOD₅, NH₄⁺-N, TN, and TP, while grab samples were collected for TSS to capture short-term fluctuations. All samples were preserved at 4 °C and analyzed within 24 h in accordance with Standard Methods [26].

Analytical Procedures

- COD and BOD₅ were determined by dichromate reflux digestion and respirometric analysis, respectively.
- NH₄⁺-N, TN and TP were quantified using spectrophotometric methods (Hach DR3900) with appropriate digestion steps where required.
- TSS was measured gravimetrically using pre-weighed glass microfiber filters (Whatman GF/C, 1.2 μm).
- DO was continuously monitored in situ using YSI optical probes (Model ProDSS) to support aeration control.
- Energy consumption was monitored via digital power meters (Siemens PAC2200 series) installed

on the aeration blower and auxiliary mixing circuits. Monthly electricity use (kWh) was normalized by the corresponding treated flow to obtain specific aeration energy (kWh m⁻³).

Sludge Quantification and Data Normalization:

Excess sludge production was quantified from waste-sludge total solids (TS) and volatile solids (VS) analyses and reported as sludge yield (kg VSS kg⁻¹ COD removed). Key indicators were normalized as follows:

- Removal efficiency (%):

$$\frac{C_{In} - C_{Out}}{C_{In} \times 100} \text{ for each parameter} \quad (1)$$
- Specific aeration energy (kWh m⁻³): monthly blower/mixer kWh divided by treated flow;
- Energy intensity (kWh kg⁻¹ COD removed): specific energy divided by COD removed per unit volume.

Statistical Analysis

Descriptive statistics (mean, range) were computed for each monitoring period. Normality was screened using the Shapiro–Wilk test. Differences between EA and MBBR effluent quality were evaluated using two-sided Welch’s t-tests ($\alpha = 0.05$) because variances were not assumed equal. For multi-parameter comparisons, one-way ANOVA was used where applicable. Pearson correlation was applied to explore relationships among operational variables. Outliers were screened using Grubbs’ test and by verification against duplicate measurements and instrument calibration records. This monitoring and analytical protocol provided a quantitative and reproducible basis for assessing full-scale system performance before and after the MBBR retrofit.

2.5 Kinetic Performance Modelling and Capacity Projection

To provide a transferable numerical interpretation of the full-scale retrofit, an apparent first-order completely mixed reactor (CSTR) model was used to back-calculate removal-rate constants from measured mean influent/effluent concentrations and hydraulic retention time (HRT). For a generic constituent C (e.g., COD or NH₄⁺-N), the steady-state mass balance yields:

$$C_{out} = \frac{C_{in}}{(1 + k \times HRT)} \quad (2)$$

where k (time⁻¹) is the apparent first-order removal coefficient. k was estimated for each process using:

$$k = \frac{C_{in}}{(C_{out} - 1)} \times \frac{1}{HRT} \quad (3)$$

The calibrated k values were then used to numerically project the HRT required to meet target effluent concentrations (e.g., COD ≤ 100 mg L⁻¹ and NH₄⁺-N ≤ 10 mg L⁻¹) under steady-state assumptions:

$$HRT_{req} = \frac{C_{In}}{(C_{target} - 1)} \times \frac{1}{k} \quad (4)$$

This simplified model is not intended to replace mechanistic activated-sludge models (e.g., ASM families), but it provides a compact numerical basis for comparing process intensification between EA and MBBR within a single full-scale case study.

In addition, a dimensionless performance index (PI) was computed from normalized scores for effluent quality,

sludge production, energy and operational stability (Table 3), enabling transparent cross-study comparison and integration with the scoring heatmap:

$$PI = \frac{(\sum w_i \times S_i)}{(\sum w_i)} \quad (5)$$

where S_i is the score (1–5) for criterion i and w_i is its weight (set to 1.0 for equal weighting in this study).

Table 3: Performance scoring framework for MBBR vs. EA (COD/BOD removal, sludge yield, energy efficiency, operational stability). Energy efficiency is evaluated using energy intensity (kWh kg^{-1} COD removed). Score thresholds are based on commonly reported benchmarks for secondary biological treatment and MBBR retrofits [10,11,14,37].

Criterion	Score 5 (Excellent)	Score 4 (Good)	Score 3 (Moderate)	Score 2 (Low)	Score 1 (Poor)
Organic Removal (COD/BOD)	>90% stable removal	75–85% stable	60–75%, some fluctuations	<60%	Very poor removal
Sludge Yield	>70% reduction vs EA	50–70% reduction	30–50% reduction	<30% reduction	No reduction
Energy Efficiency	>30% reduction vs EA	20–30% reduction	<20% reduction	Similar to EA	Higher than EA
Operational Stability	Very stable, no issues	Minor issues, manageable	Moderate issues (clogging, detachment)	Frequent operational problems	Unstable operation

3. Results and Discussion

3.1 Effluent Quality and Treatment Efficiency

Comparative analyses of influent and effluent data before and after the upgrade highlighted substantial reductions in organic matter, nutrients, and suspended solids, consistent with those expected from biofilm-based systems. Influent and effluent concentrations for the key monitored parameters are summarized in Fig. 2, and the corresponding removal efficiencies are presented in Fig. 3. The reductions in effluent concentrations between EA and MBBR periods were statistically significant for all monitored parameters (Welch's t-test; p-values reported in Table 4).

Table 4: Statistical comparison of EA vs MBBR effluent quality (Welch's t-test).

Parameter	EA effluent mean (mg/L)	MBBR effluent mean (mg/L)	Change vs EA (%)	p-value (Welch t-test)
COD	225.0	90.0	-60.0%	1.94e-46
BOD ₅	100.0	40.0	-60.0%	5.59e-37
NH ₄ ⁺ -N	22.5	10.0	-55.6%	2.11e-54
TN	30.0	15.0	-50.0%	9.92e-39
TP	5.0	3.0	-40.0%	6.61e-28
TSS	70.0	27.5	-60.7%	5.25e-38

Note: p-values were computed using Welch's t-test on $n = 36$ composite samples per period (3 samples/week \times 12 weeks). All parameters showed statistically significant improvements ($p < 0.001$).

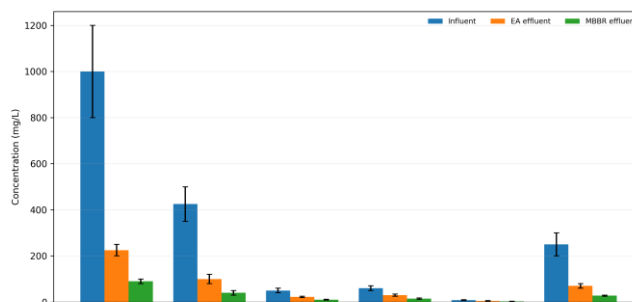


Fig. 2: Influent and effluent concentrations (mean with min-max range) for chemical oxygen demand (COD), biochemical oxygen demand (BOD₅), ammonium nitrogen (NH₄⁺-N), total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) under extended aeration (EA) and moving bed biofilm reactor (MBBR) operation.

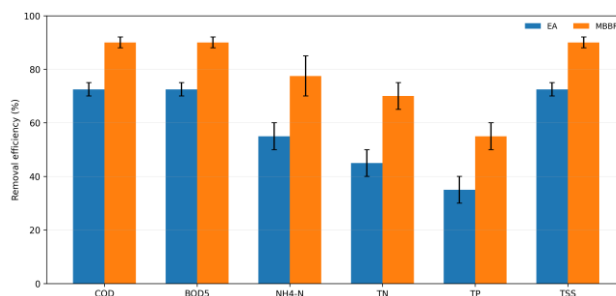


Fig. 3: Removal efficiencies (mean with min-max range) for COD, BOD₅, NH₄⁺-N, TN, TP, and TSS under EA and MBBR operation at Nikan Hospital WWTP.

Hospital wastewater typically exhibits elevated nitrogen loads and can experience strong diurnal variability. In the EA baseline, ammonium removal efficiency averaged 50–60%, indicating incomplete nitrification under fluctuating loading. By contrast, the MBBR process achieved 70–85% NH₄⁺-N removal and maintained effluent nitrate

concentrations below 15 mg/L, confirming robust nitrification. Denitrification was also improved, following the introduction of an anoxic zone, with TN removal increasing from 40–50% (EA) to 65–75% (MBBR). TP removal improved moderately from 30–40% (EA) to 50–60% (MBBR), consistent with enhanced biomass retention and biofilm-mediated uptake; however, additional (chemical or enhanced biological) phosphorus removal would be required where very stringent P limits apply [1,27]. Overall, the improved effluent quality indicates that compact MBBR retrofitting can bring hospital WWTPs closer to typical secondary-treatment discharge targets for organics and suspended solids. For reuse applications, further disinfection and/or polishing steps are commonly required to manage pathogens and persistent micropollutants, which were not directly measured in the present monitoring program [28].

3.2 Process Dynamics and Biofilm Performance

After retrofitting the EA system to MBBR at Nikan Hospital WWTP, carriers were colonized within 3–4 weeks, forming a stable biofilm. This colonization enhanced the biomass retention and enabled the consistent nitrification even under shock loads (e.g., sudden increases in COD or ammonium due to pharmaceutical discharges). In contrast, the EA system frequently exhibited fluctuations in DO and washout of nitrifiers. With the high specific surface area of carriers ($500 \text{ m}^2/\text{m}^3$), these instabilities were significantly reduced. Hydrodynamic improvements and modifications to the aeration system enhanced mixing and oxygen transfer into the biofilm. DO concentrations increased from 1.5–2 mg/L in EA to 2.5–3 mg/L in MBBR, improving COD oxidation and nitrification rates. When normalized to the effective reactor volume (excluding carrier displacement), the apparent organic loading rate (OLR) increased from 0.6–0.8 to 1.2–1.5 kg COD/ $\text{m}^3 \cdot \text{d}$ due to higher active biomass density supported by biofilm carriers, while effluent quality remained within discharge standards.

Direct microscopic or molecular analyses of biofilm communities were not conducted in this study; however, based on operational performance and literature evidence, it is inferred that microbial community dynamics differed between the systems. The enhanced nitrification and process stability observed in the MBBR are consistent with previous findings that such biofilms favor the enrichment of specialized nitrifiers such as ammonia-oxidizing and nitrite-oxidizing bacteria [14,16]. Typical biofilm thickness in similar MBBR systems has been reported in the range of 300–400 μm , which creates internal anoxic layers that facilitate partial denitrification and contribute to functional diversity.

A key improvement observed was the substantial reduction in sludge production. Excess sludge yield in MBBR was about one-fourth of EA (reduced from 0.5–0.6 kg VSS/kg COD removed in EA to 0.12–0.15 in MBBR). This reduction lowered sludge handling costs and improved operational stability.

3.3 Energy Use and Operational Cost

3.3.1 Energy Demand and Aeration Efficiency

At Nikan Hospital, the retrofit required additional aeration to provide both oxygen transfer and sufficient carrier mixing. Accordingly, the measured specific aeration energy increased modestly from 0.74 kWh/ m^3 under EA to 0.83 kWh/ m^3 under MBBR (12% increase). When normalized to pollutant removal, the energy intensity per kg COD removed decreased slightly (0.95 to 0.91 kWh kg⁻¹ COD removed) because of higher COD removal efficiency. These results are consistent with the known trade-off in MBBR systems where mixing requirements can increase aeration demand, while improved biomass retention enhances treatment efficiency [11,37].

3.3.2 Operational Costs and Sludge Management

Sludge management requirements were significantly reduced. In the EA system, excess sludge production averaged approximately 0.55 kg VSS kg⁻¹ COD removed, whereas after upgrading to MBBR the sludge yield declined to about 0.13 kg VSS kg⁻¹ COD removed. Consequently, sludge wasting and disposal frequency decreased from roughly twice weekly to approximately once every two to three weeks. This 75% reduction in sludge yield directly translates into lower sludge transport/disposal burden and fewer process interruptions associated with thickening and dewatering operations [8,9].

3.3.3 Media Replacement and Maintenance

The introduction of carrier media in MBBR incurred a one-time capital cost. For the Nikan Hospital WWTP, filling the tank with polyethylene carriers ($500 \text{ m}^2/\text{m}^3$ effective surface area) accounted for approximately 15–20% of total retrofit investment. Since MBBR carriers typically have a long service life (>15 years), the annualized replacement cost is minimal compared with recurring OPEX components. Routine maintenance was reduced because the MBBR system required less operator intervention than EA (e.g., fewer sludge-age adjustments and no lamella-clarifier clogging events). However, aeration setpoints were maintained slightly higher to ensure carrier circulation, which explains the modest increase in specific aeration energy.

3.3.4 Labor and Monitoring

Staff workload decreased after the upgrade. The EA system required frequent sludge age monitoring, MLSS adjustments, and operator interventions to maintain stability. In contrast, the MBBR process was more resilient to influent variations, reducing the need for corrective actions. Operator labor hours were reduced by an estimated 25–30%, further lowering operational expenditure.

3.3.5 Overall Cost Implications

When the effects of reduced sludge production (from approximately 0.55 to 0.13 kg VSS kg⁻¹ COD removed), lower maintenance frequency, and reduced labor requirements are considered, the overall operational expenditure (OPEX) of the MBBR system was estimated at approximately 60–65% of the EA process (35–40% reduction) on a per-cubic-meter basis. While electricity costs increased slightly due to higher aeration demand, this was more than offset by the reduction in sludge handling and labor. Although the retrofit introduced additional capital

investment (CAPEX) associated with carrier media and screening equipment, the resulting long-term savings indicate a payback period of approximately 3–4 years. The distribution of capital and operating cost components for EA and MBBR is illustrated in Fig. 4.

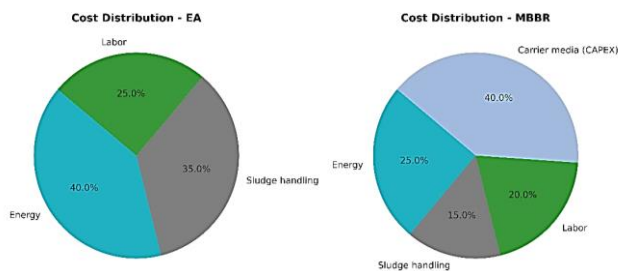


Fig. 4: Operational and capital cost distribution for EA and MBBR systems at Nikan Hospital WWTP.

3.4 Sludge Characteristics and Management

3.4.1 Excess Sludge Production

One of the most notable improvements after upgrading from EA to MBBR at Nikan Hospital WWTP was the significant reduction in excess sludge generation. In the EA system, sludge yield averaged 0.50–0.60 kg VSS/kg COD removed, typical of EA processes where high sludge age results in relatively high biomass production. After conversion to MBBR, sludge yield decreased to 0.12–0.15 kg VSS/kg COD removed, representing a 75% reduction. This decrease is consistent with biofilm-based systems, where part of the biomass is retained within carrier-attached communities and endogenous respiration is more dominant [8,9].

3.4.2 Sludge Handling and Operational Needs

With reduced sludge production, the frequency of sludge withdrawal and off-site disposal decreased substantially. Under EA operation, sludge wasting was typically performed roughly twice per week, whereas after conversion to MBBR sludge wasting was generally required only once every 2–3 weeks. Because waste-sludge solids concentration can vary with thickening/dewatering practice, sludge reduction is reported primarily via the yield metric (kg VSS kg⁻¹ COD removed), which decreased from 0.50–0.60 (EA) to 0.12–0.15 (MBBR).

3.4.3 Sludge Characteristics

Although no microscopic images were obtained in this study, settling tests and operational observations indicated that sludge from the MBBR system was denser and more compact than that from the EA process. The Sludge Volume Index (SVI), determined through standard settling tests, decreased from approximately 180–200 mL g⁻¹ under EA to 90–110 mL g⁻¹ in MBBR, confirming improved settleability and dewaterability that reduced sludge handling costs.

3.4.4 Environmental and Economic Implications

Although no formal Life Cycle Assessment (LCA) was conducted, the observed 75% reduction in sludge volume and the 35–40% decrease in overall operating costs (OPEX) indirectly lowered the environmental burden of the WWTP. Assuming an average transport distance of 20 km

for sludge disposal and a diesel consumption rate of 0.3 L km⁻¹ truck⁻¹, the reduction in sludge hauling frequency is estimated to have cut fuel use by roughly 200–250 L month⁻¹ (0.6 t CO₂ month⁻¹). This simplified estimate indicates a measurable decrease in the facility's carbon footprint and supports improved sustainability for space-limited hospital sites such as Nikan [29].

3.5 System Design Considerations

3.5.1 Hydraulic Retention Time (HRT)

In the EA system at Nikan Hospital, the nominal hydraulic retention time (HRT) was approximately 24 h based on the reactor volume and average influent flow rate. Following the upgrade to MBBR, the physical reactor volume remained unchanged, but the effective biological capacity increased due to the additional active surface area provided by the biofilm carriers. This enhancement enabled stable treatment at throughput levels equivalent to an apparent HRT of about 9 h during peak loading periods, while maintaining the improved effluent quality shown in Figs. 2–3. On a purely hydraulic basis, reducing HRT from 24 to 9 h corresponds to a theoretical capacity increase of about 2.7× at constant volume (24/9), although the realized increase is bounded by upstream/downstream units and actual hospital wastewater generation.

3.5.2 Footprint and Space Utilization

Although the physical footprint of the WWTP remained unchanged, the MBBR configuration substantially increased the effective volumetric treatment capacity by enhancing biomass retention within the same tank volume. For hospitals where land availability is limited, this type of process intensification is advantageous because it increases treatment capacity per unit area without civil expansion. In practice, the Nikan Hospital plant was able to accommodate substantially higher peak hydraulic and organic loads than under EA operation without deterioration in effluent quality.

3.5.3 System Scalability

To provide a transferable quantitative interpretation of this capacity gain, the apparent first-order kinetic model which is described in Section 2.5 was back-calculated using the measured mean influent/effluent concentrations and the corresponding HRTs (as shown in Fig. 5). The resulting apparent removal coefficients (k) and the HRTs required to meet representative target effluent concentrations are summarized in Table 5. The model indicates that, for COD ≤ 100 mg L⁻¹, the required HRT decreases from 63 h (EA) to 8 h (MBBR), while for NH₄⁺-N ≤ 10 mg L⁻¹ it decreases from 79 h (EA) to 9 h (MBBR). These model-based projections support the observed ability of the retrofit to operate reliably at an apparent HRT of 9 h without adding tank volume. Further scalability is possible by increasing the carrier fill fraction from the current 40% to approximately 55% (subject to aeration capacity and screen design), consistent with reported ranges for full-scale MBBR systems [14,16]. Key design and operational indicators comparing EA and MBBR are summarized in Fig. 6.

Table 5: Apparent first-order kinetic coefficients (Eq. 3) and projected HRT requirements (Eq. 4) for representative target effluent concentrations.

Parameter	Target C _{out} (mg/L)	k _{EA} (h ⁻¹)	k _{MBBR} (h ⁻¹)	HRT _{req, EA} (h)	HRT _{req, MBBR} (h)
COD	100	0.144	1.123	62.7	8.0
NH ₄ ⁺ -N	10	0.051	0.444	78.5	9.0

Note: k values were back-calculated from monitored mean C_{in} and C_{out} (Fig. 2) and observed HRTs (24 h for EA; 9 h for MBBR).

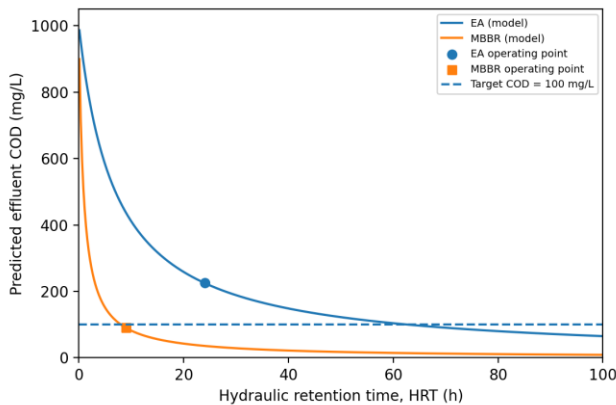


Fig. 5: First-order CSTR model projection of effluent COD versus HRT for EA and MBBR at Nikan Hospital.

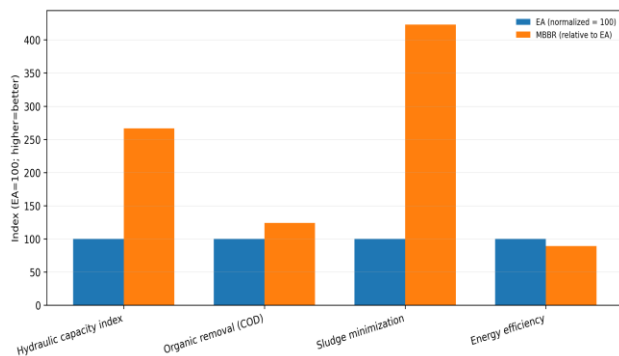


Fig. 6: Comparative summary of key design and operational indicators for EA versus MBBR at Nikan Hospital WWTP (hydraulic retention time, relative treatment capacity, sludge yield, and specific aeration energy).

3.6 Practical Observations and Operational Challenges

3.6.1 Startup and Acclimation

Following the transition from EA to MBBR at Nikan Hospital, an acclimation period was required for biofilm development on the carriers. During the first 4–6 weeks, COD and BOD removal efficiencies were lower than the long-term average, primarily due to gradual colonization of the media. By the end of the second month, stable biofilm growth was established, and effluent quality consistently met discharge standards. Operators noted that seeding with a portion of existing activated sludge accelerated startup and reduced risks of early performance decline.

3.6.2 Biofilm Detachment and Stability

Occasional episodes of biofilm detachment were observed, particularly during periods of elevated aeration intensity under peak loads. During these events, effluent TSS temporarily increased from 25–30 mg L⁻¹ (mean 28 mg L⁻¹) to 35–45 mg L⁻¹, remaining elevated for less than 48 hours before returning to baseline. The system re-stabilized within 24–48 hours as biofilm communities reattached. Minor adjustments to aeration rates ($\pm 10\%$) and maintaining steady hydraulic conditions effectively minimized excessive sloughing in subsequent cycles.

3.6.3 Clogging and Carrier Performance

A potential operational concern was clogging in screens and recirculation lines due to carrier accumulation. At Nikan Hospital, this risk was systematically monitored through biweekly visual inspections over a six-month period. No clogging events were recorded. The stainless-steel outlet sieves (mesh size = 4 mm) effectively retained the Kaldnes K3 media, while maintaining a stable headloss below 5 cm. Aeration was maintained at the site setpoint (approximately 25–30 m³ h⁻¹), sufficient to keep carriers in full suspension without surface overflow. The polyethylene media (500 m² m⁻³ effective surface area) preserved uniform buoyancy and mechanical integrity, with no measurable weight loss (<1%) or deformation throughout the observation period.

3.6.4 Operator Feedback and Practical Insights

Compared to the EA process, the MBBR system required substantially fewer manual interventions. During the first two months of operation, operators performed daily checks of aeration flow and DO levels (target 2.5–3.0 mg L⁻¹) to optimize carrier mixing and prevent under- or over-aeration. Once biofilm growth stabilized, inspection frequency decreased to once every 3–4 days, and sieve cleaning was needed only once per week compared with every 2 days under EA. Continuous DO monitoring confirmed stable oxygen profiles, maintaining fluctuations within ± 0.3 mg L⁻¹. Overall, the Nikan Hospital MBBR retrofit showed that although the startup phase required intensive monitoring for roughly 6 weeks, the system subsequently achieved steady operation with >95 % uptime and minimal intervention. Occasional operational challenges—such as transient biofilm detachment or sieve fouling—were resolved through minor aeration adjustments (<10 % airflow change) without affecting effluent quality or long-term performance. A comparative summary of operational challenges and relative performance scores is provided in Fig. 7.

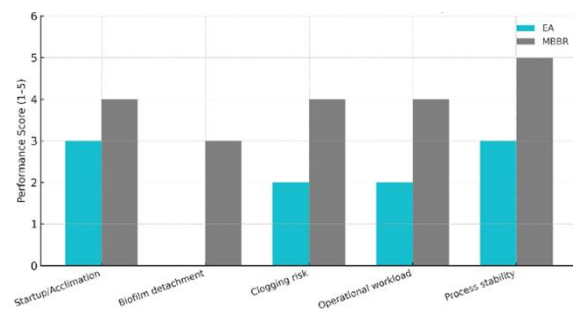


Fig. 7: Comparative operational challenges and performance scores for EA and MBBR systems at Nikan Hospital.

3.7 Trade-Offs and Optimization

3.7.1 Energy vs. Treatment Efficiency

At Nikan Hospital, the transition from EA to MBBR substantially improved treatment efficiency and stability, while requiring a modest increase in specific aeration energy. Under EA, average COD and BOD₅ removal efficiencies were approximately 70–75% (Fig. 3), and effluent COD occasionally approached 250 mg L⁻¹ during peak hospital activity (Fig. 2). After the upgrade, the MBBR process achieved stable COD and BOD removal efficiencies above 90%, with a marked reduction in effluent variability (coefficient of variation of effluent COD reduced from 22% under EA to 6% under MBBR). Specific aeration energy increased from 0.74 to 0.83 kWh m⁻³, reflecting carrier mixing and higher oxygen-transfer demand; nevertheless, because sludge yield and operator workload decreased substantially, overall OPEX declined to 60–65% of EA. The results therefore illustrate a practical MBBR trade-off: slightly higher aeration demand in exchange for higher process resilience, compactness, and more reliable effluent quality.

3.7.2 Capital Investment vs. Long-Term Operational Savings

The retrofit required additional capital investment primarily for carrier media, reactor sieves, and minor civil/mechanical modifications. Relative to maintaining the EA system, CAPEX increased by approximately 20–25% because of carrier-media procurement and installation. Nevertheless, reduced sludge production and operating workload lowered long-term OPEX to approximately 60–65% of EA, yielding an estimated payback period of 3–4 years and more than two-fold cumulative savings over a 10-year horizon, confirming both technical and economic viability of the retrofit.

3.7.3 Optimization Perspective

From an operational standpoint, the optimization achieved at Nikan Hospital demonstrates that MBBR technology can balance short-term capital costs with long-term economic and environmental benefits. The system not only reduced operational burdens but also increased resilience against load fluctuations, which is particularly valuable in hospital wastewater treatment where variability is high. The principal trade-offs between EA and MBBR identified in this study are illustrated in Fig. 8.

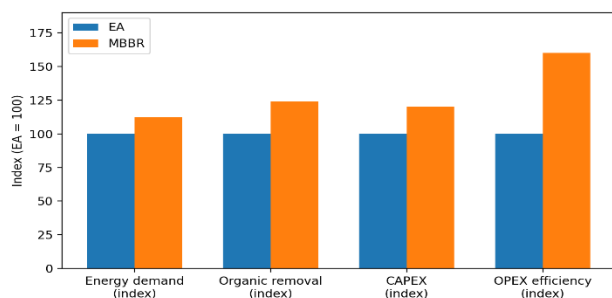


Fig. 8: Trade-offs between EA and MBBR at Nikan Hospital shown as normalized indices (EA = 100): energy demand, COD/BOD removal performance, capital cost, and long-term savings.

3.8 Environmental and Sustainability Impacts

3.8.1 Carbon Footprint and Compliance Improvements

Carbon footprint implications were assessed qualitatively using the measured energy demand and the observed reduction in sludge hauling. While specific aeration energy increased modestly after media installation, the substantial reduction in sludge withdrawal and transportation frequency is expected to reduce the overall greenhouse-gas burden of the facility. A full life-cycle assessment is recommended for future work.

3.8.2 Potential for Water Reuse

This reuse potential could reduce municipal-water demand; however, site-specific economic savings should be evaluated using local water tariffs, additional tertiary treatment requirements, and reuse-distribution constraints.

3.8.3 Nutrient Recovery

Although nutrient concentrations in hospital wastewater are typically moderate compared with large municipal flows, the improved nitrification–denitrification performance of the MBBR process provides a quantitative basis for future nutrient-management options. Based on the monitored effluent ranges after retrofit (TN 12–18 mg L⁻¹; NH₄⁺-N 8–12 mg L⁻¹; TP 2–4 mg L⁻¹; Fig. 2), the plant currently discharges on the order of 2.4–3.6 kg N day⁻¹ and 0.4–0.8 kg P day⁻¹ at an average flow of 200 m³ day⁻¹. Depending on the reuse/discharge strategy, future upgrades could evaluate polishing and/or recovery options (e.g., targeted ammonia removal or phosphorus precipitation).

3.8.3 Overall Sustainability Perspective

Overall, the MBBR upgrade has improved the system's sustainability profile by reducing the sludge hauling demand and stabilizing effluent quality. The net carbon-footprint change depends on site-specific electricity and transport emission factors. Improved effluent consistency also supports potential non-potable reuse; however, safe reuse would require site-specific risk assessment and additional disinfection/polishing, particularly for pathogens and emerging contaminants that were not directly monitored in this study. A comparative sustainability assessment of EA and MBBR is summarized in Fig. 9.

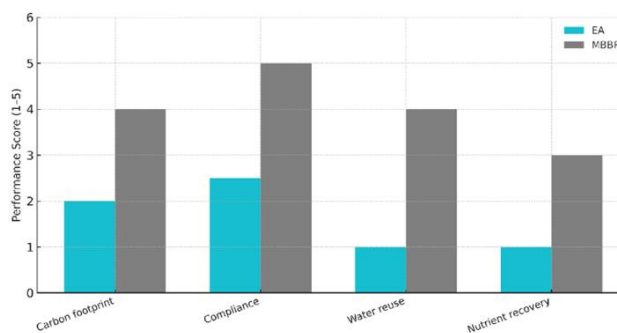


Fig. 9: Environmental and sustainability performance comparison of EA vs. MBBR at Nikan Hospital (carbon footprint, compliance, water reuse, nutrient recovery).

3.9 Comparison to Literature and Broader Implications

3.9.1 Alignment with Existing Literature

The results obtained at Nikan Hospital after the transition from EA to MBBR were broadly consistent with international findings, while also reflecting site-specific characteristics of compact hospital plants. In line with the design and operation principles summarized by Rusten and Ødegaard [14] and recent reviews of MBBR field performance [37], the retrofit achieved COD and BOD₅ removal above 90% and reduced sludge yield by 75% relative to EA (from 0.55 to 0.13 kg VSS kg⁻¹ COD removed). The modest increase in specific aeration energy observed in this case (from 0.74 to 0.83 kWh m⁻³) is also consistent with the well-known requirement for sufficient aeration to maintain carrier suspension at practical filling fractions. Importantly, improved biomass retention and process stability enabled operation at a substantially lower effective HRT (from 24 h to 9 h), demonstrating process intensification within the same footprint. These outcomes complement prior applications of MBBR for challenging industrial wastewaters (e.g., formaldehyde and petroleum effluents) [31,32], highlighting the versatility of attached-growth systems under inhibitory or variable loading.

3.9.2 Contrasts and Site-Specific Differences

Unlike several large municipal MBBR installations where persistent biofilm detachment and clogging can become recurring issues [15], the Nikan Hospital retrofit experienced only occasional short-term screen fouling or transient biofilm sloughing. These events were manageable through minor aeration adjustments and routine sieve cleaning, without compromising the overall effluent quality during the monitoring period. The relatively small system scale (200 m³ d⁻¹) and lower peak hydraulic variability compared with municipal facilities likely reduced mechanical stress and detachment frequency.

Lessons for Similar Hospital WWTPs and Study Contributions:

- Scalability and footprint: MBBR retrofitting can be implemented effectively where spatial constraints prevent tank expansion, enabling process intensification by increasing effective biomass retention rather than increasing volume.
- Operational resilience: The attached-growth configuration buffered organic and hydraulic variability typical of healthcare facilities, reducing the need for corrective operator actions.
- Energy–sludge trade-off: While aeration demand can increase to maintain carrier mixing, the large reduction in excess sludge yield can outweigh this penalty in overall OPEX.
- Design-oriented transferability: By back-calculating an apparent kinetic model from **full-scale data** (Section 2.5 and Fig. 5), this study provides a simple design-oriented pathway for

translating case-study outcomes into design HRT targets.

- Emerging contaminants: Pharmaceuticals and pathogens were not directly measured; however, published evidence indicates that staged MBBR systems can contribute to biodegradation of some pharmaceuticals [21,22]. For safe reuse, additional disinfection and/or advanced polishing (e.g., AOP, activated carbon, membrane filtration, or microalgal post-treatment) should be evaluated in future work [35].

Overall, the Nikan Hospital case reinforces the evidence that MBBR retrofits can outperform conventional EA in terms of effluent quality stability, sludge minimization, and footprint efficiency, while incurring only a modest aeration-energy penalty. The simplified performance scoring framework used for the comparative assessment is provided in Table 3, and a benchmarked performance heatmap is presented in Fig. 10. To improve transparency, the score thresholds in Table 3 were selected to reflect commonly reported secondary-treatment performance ranges and energy/sludge benchmarks in the literature [10,11,14,37].

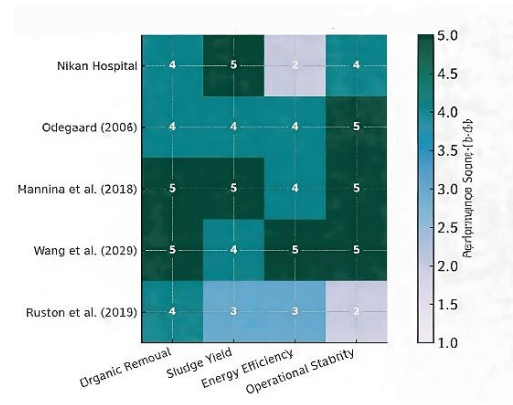


Fig. 10: Heatmap comparison of Nikan Hospital WWTP performance (EA vs. MBBR) against literature benchmarks [14,15]

4. Conclusion

Upgrading the Nikan Hospital wastewater treatment plant from extended aeration to a moving bed biofilm reactor (MBBR) configuration has improved the treatment performance and operational efficiency without requiring civil expansion. Across the post-retrofit monitoring period, the MBBR achieved consistently better effluent quality (notably for COD, BOD₅ and ammonia), higher resilience to the hydraulic and organic load fluctuations typical of hospital discharges, and more stable process control due to biofilm retention on the carriers.

From an operational and economic perspective, the retrofit achieved substantial sludge minimization and improved effluent stability, which translated into lower overall operating costs and a favorable payback horizon relative to maintaining or expanding the conventional EA process. Although specific aeration energy increased modestly to

satisfy carrier-mixing requirements, the reduction in sludge handling and operator workload drove the net OPEX savings. In practice, MBBR retrofits are most advantageous for space-constrained facilities, plants with pronounced peak loads, and sites facing sludge-handling limitations. Successful implementation depends on appropriate carrier selection and fill fraction, reliable media-retention screens, sufficient aeration capacity to satisfy both oxygen demand and mixing, and gradual ramp-up supported by routine monitoring of DO, ammonia and solids to prevent media loss or biofilm overgrowth.

Key limitations of the present study include the single-site scale, the finite monitoring window, and the lack of direct measurements for micropollutants and pathogenic indicators that are particularly relevant for hospital effluents. Future work should extend performance monitoring across seasons, incorporate pharmaceutical and microbial risk indicators, and evaluate hybrid options (e.g., IFAS/MBR integration) and automation strategies to further improve compliance reliability and energy resilience under tightening discharge standards.

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