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Comprehensive Evaluation of Wastewater Treatment Performance in 59 Hospitals in Tehran: An Innovative Approach to Compliance Assessment and Hospital Wastewater Management

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Abstract

Introduction: Hospitals generate substantial volumes of highly contaminated wastewater, posing serious environmental and public health concerns. Hospital wastewater (HWW) contains pharmaceutical residues, heavy metals, disinfectants, pathogens, and antibiotic-resistant bacteria, many of which are not completely removed by conventional wastewater treatment plants (WWTPs).

Methods: This study evaluated the performance of hospital WWTPs in Tehran, Iran. A total of 128 effluent samples were collected in 2024 from 59 hospital WWTPs affiliated with Iran University of Medical Sciences. Samples were analyzed to assess treatment efficiency using key physicochemical and microbiological parameters, including biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), total coliforms, and fecal coliforms, according to standard methods.

Results: All hospitals operated wastewater treatment systems; however, 8.33% consistently failed to comply with national effluent discharge standards. Regarding disposal routes, 66.6% of effluents were discharged into municipal sewer systems, 21.6% into infiltration wells, and 11.6% were reused for irrigation.

Conclusion: Despite the presence of treatment systems, deficiencies in pollutant removal and improper discharge practices remain concerns. Ensuring full connection of hospital WWTPs to municipal sewer networks would enable further treatment at centralized facilities, reducing environmental and health risks. Strengthened regulatory enforcement and adoption of advanced treatment technologies are essential to improve hospital wastewater management and safeguard public health.

Keywords: Wastewater, Hospitals, Quality, Environmental health, Pollution

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Introduction

Hospitals are essential healthcare facilities that provide critical medical services, research, and patient care; however, they also generate a significant amount of highly contaminated wastewater, posing severe environmental and public health challenges (1,2). Hospital wastewater (HWW) is a complex matrix containing a variety of hazardous substances, including pharmaceutical residues, persistent organic pollutants, heavy metals, disinfectants, pathogens, and antibiotic-resistant bacteria, which can have long-term ecological and epidemiological consequences (3,4).

Hospital wastewater (HWW) is typically characterized by high concentrations of key pollution indicators, including biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), ammonia nitrogen, organic nitrogen, nitrites, nitrates, total phosphorus, and total suspended solids. In addition to chemical pollutants, HWW contains significant amounts of pathogenic microorganisms such as bacteria, viruses, protozoa, and fungi, as well as antibiotic resistance genes (ARGs) and antibiotic-resistant bacteria (ARB).

Numerous studies have shown that the concentrations of these constituents in HWW are generally higher than those found in municipal wastewater (MWW). Moreover, the average biodegradability index (BOD/COD ratio) in HWW is typically lower than in MWW, indicating the difficulty of treating HWW using conventional biological treatment methods. This reduced biodegradability is mainly due to the presence of toxic and non-biodegradable compounds such as pharmaceutically active compounds (PhACs), X-ray contrast media, surfactants, and persistent disinfectants. Many of these substances, classified as emerging contaminants (ECs), possess high environmental persistence and can exert toxic effects on humans and aquatic organisms even at very low concentrations (in the nanogram to microgram per liter range) (5-7).

The composition and volume of HWW depend on several factors, such as hospital size, bed capacity, the nature of medical services provided, patient turnover, and geographic conditions (8,9). Unlike municipal wastewater, HWW is characterized by a high concentration of bioactive and toxic compounds, including cytostatic drugs, antibiotics, analgesics, and contrast agents, which are frequently detected at concentrations ranging from nanograms to micrograms per liter (10,11). Studies have documented the persistence of these compounds in aquatic environments due to their incomplete removal in conventional wastewater treatment plants (WWTPs), leading to their accumulation in surface and groundwater, potentially affecting human health through drinking water sources (12,13).

According to the World Health Organization (WHO), Iran ranks among the top 20 drug-consuming countries globally, holding the second position in Asia after China. The per capita drug consumption in Iran is three times the global average, with antibiotic consumption being 14 to 16 times higher than the global standard. Studies have shown that antibiotics are not fully metabolized in the human body, with 30–90% excreted in an active form. Consequently, between 30,000 and 180,000 tons of active antibiotics are introduced into the environment each year (14).

One of the major concerns regarding HWW discharge is its contribution to the spread of antimicrobial resistance (AMR). The presence of residual antibiotics and resistant microbial strains in untreated or inadequately treated hospital effluents facilitates the selection and proliferation of antibiotic-resistant genes (ARGs), which can be transferred to pathogenic bacteria, exacerbating the global AMR crisis (15,16). Moreover, the occurrence of endocrine-disrupting chemicals (EDCs) and genotoxic substances in hospital effluents has raised concerns about their potential impact on aquatic ecosystems and human health (17,18). A recent study by Esmaeili-Khoshmardan et al. (2024) has demonstrated the presence of resistant bacteria such as *E. coli* and *P. aeruginosa* at concentrations of 6.78×10^5 CFU/mL in the influent of hospital wastewater in Tehran. The study evaluated the impact of biological treatment and coagulation-settling processes on the reduction of microbial resistance load and reported that high levels of BOD and nitrate can increase the survival of these microorganisms in treatment systems (19).

The study by Zhang et al. (2021) examined the limited efficiency of activated sludge systems in removing resistant bacteria and showed that even after standard treatment processes, significant quantities of resistant bacteria remained, indicating the need for additional processes such as UV or ozonation (20). The study by Chen et al. (2022) showed that higher organic loads and nitrate concentrations directly influenced the survival of antibiotic-resistant bacteria in hospital wastewater treatment systems. The researchers recommended stricter control of these parameters to enhance microbial removal efficiency (21). Hospital wastewater treatment remains a significant challenge, especially in developing countries where inadequate infrastructure, lack of stringent regulations, and limited financial resources hinder the effective management of hazardous effluents (22-24). Conventional wastewater treatment methods, such as activated sludge processes, are often insufficient for the complete removal of pharmaceutical compounds, necessitating the implementation of advanced treatment technologies. Among these, advanced oxidation processes (AOPs), membrane filtration techniques (e.g., reverse osmosis and nanofiltration), and constructed wetlands have shown promising results in degrading or removing persistent contaminants from the HWW (25,26). Luo et al. investigated the effectiveness of combined coagulation–sedimentation and advanced oxidation processes (AOPs) for the removal of antibiotic resistance genes (ARGs) from hospital wastewater. Their findings revealed a significant reduction in microbial load and substantial improvement in effluent quality (27). Despite the growing recognition of the environmental risks associated with hospital effluent discharge, there remains a scarcity of comprehensive studies evaluating the performance of hospital wastewater treatment plants (WWTPs), particularly in low- and middle-income countries (28,29). Insufficient data on treatment efficiency, coupled with the absence of standardized monitoring protocols, has led to regulatory gaps and challenges in risk assessment (30,31). Therefore, a systematic assessment of HWW treatment efficiency is crucial for informing policy decisions and optimizing wastewater management strategies (32). The study by Mesdaghinia et al. (2008) reported that the average influent concentrations of BOD_5 and COD in hospital wastewater were approximately 348 and 527 mg/L, respectively. After treatment using activated sludge systems, these values were reduced to 113 mg/L for BOD_5 and 188 mg/L for COD. However, the effluent concentrations still exceeded the national environmental standards of Iran ($BOD < 50$ mg/L and $COD < 100$ mg/L), indicating the need for supplementary treatment processes or upgrades to the existing technologies (33). Meriem Krouma et al. (2022) conducted a study titled "Assessment and spatial mapping of treated wastewater quality for safe agricultural reuse in Tunisia." This research evaluated the quality of treated wastewater across Tunisia by analyzing seven physicochemical parameters including total suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand over five days (BOD5), cadmium, and lead, and five microbiological parameters, including faecal coliforms, faecal streptococci, Salmonella spp., Vibrio cholerae, and helminth eggs. The study analyzed 81 samples from 27 wastewater treatment plants (WWTPs) collected between 2017 and 2018. Compliance with standards was observed in only 11.11% (COD), 14.80% (BOD5), and 18.50% (TSS) of the WWTPs. While cadmium, lead, and Vibrio cholerae were completely removed, faecal indicators did not meet safety standards. Spatial mapping and multiple correspondence analysis highlighted the need for improved treatment and tertiary processes to eliminate microbiological contamination effectively (34). Given these concerns, this study aimed to evaluate the performance of hospital wastewater treatment plants (WWTPs) in Tehran, Iran, by assessing their ability to comply with the national and international environmental standards. By analyzing key physicochemical and microbiological parameters, this research provides a data-driven assessment of hospital wastewater management efficiency. This study, conducted in 59 hospitals in Tehran, Iran, in 2024, contributes to evidence-based policy recommendations for improved treatment strategies and the mitigation of associated environmental and public health risks.

Materials and Methods

This descriptive-analytical study was conducted in 2024 to evaluate the performance of 59 hospital wastewater treatment plants (WWTPs) affiliated with Iran University of Medical Sciences (IUMS) in Tehran, Iran. The study aimed to assess the efficiency of these treatment plants in meeting environmental discharge standards.

Data collection

Data collection was carried out through structured interviews, field observations, and wastewater sampling. A questionnaire was developed to obtain general information about the hospitals, including geographic location, year of establishment, number of wards and beds (both approved and operational), average bed occupancy rate, total staff count, and wastewater management details such as disposal methods, treatment technologies, budget allocations, and personnel involved. Interviews were conducted with relevant hospital officials to supplement the collected data.

Field visits were performed to assess the operational conditions of the WWTPs and the wastewater disposal methods. Wastewater sampling was conducted exclusively at the effluent discharge points of the treatment plants, and no influent samples were collected. A total of 128 effluent samples were obtained using grab sampling methods over different seasons. During sample collection, pH and temperature were measured on-site.

Analytical methods

The collected wastewater samples were analyzed according to the Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WEF, 23rd edition, 2017). All analyses were performed in triplicate to ensure accuracy and reproducibility, and quality assurance/quality control (QA/QC) measures, including the use of blanks and standards, were implemented throughout. The analytical procedures for each parameter are described below:

- Biochemical Oxygen Demand (BOD_5) was determined using the 5-day respirometric method (Standard Method 5210B). The samples were incubated at 20 ± 1°C in the absence of light to prevent photosynthetic oxygen production. Dissolved oxygen depletion was continuously measured with a respirometric BOD meter (WTW OxiTop®, Germany). The results were expressed in mg/L O_2.
- Chemical Oxygen Demand (COD) was analyzed by the closed reflux colorimetric method (Standard Method 5220D). Each 2 mL sample was digested with potassium dichromate and concentrated sulfuric acid at 150°C for 2 hours in a COD reactor (Hach DRB200, the USA). After digestion, absorbance was measured at 600 nm using a spectrophotometer (Hach DR3900, USA). The COD concentration was calculated against a calibration curve prepared with standard potassium hydrogen phthalate solutions.
- Total Suspended Solids (TSS) were determined gravimetrically (Standard Method 2540D). A known volume of sample was filtered through pre-weighed glass fiber filters (Whatman GF/C, 1.2 µm pore size). Filters were dried at 103–105°C to constant weight, cooled in a desiccator, and reweighed. The difference in weight was recorded as mg/L TSS.
- Total and Fecal Coliforms were quantified by the multiple-tube fermentation technique (Standard Method 9221B/E). For presumptive tests, Lauryl Tryptose Broth (LTB) was used in three-tube series with different dilutions. Positive tubes were confirmed using EC broth, with incubation at 35 ± 0.5°C for total coliforms and 44.5 ± 0.2°C for fecal coliforms. The results were expressed as Most Probable Number (MPN) per 100 mL of sample.
- Turbidity was measured by the nephelometric method (Standard Method 2130B) using a turbidimeter (Hach 2100N, the USA), which measures light scatter at 90° angle. Calibration was performed with Formazin standards. The results were expressed in Nephelometric Turbidity Units (NTU).
- Total Dissolved Solids (TDS) were determined gravimetrically (Standard Method 2540C). The filtrate was evaporated in a pre-weighed dish and dried at 180 ± 2°C until constant weight. The values were reported as mg/L.
- Nitrate (NO_3^-) was measured using the cadmium reduction method (Standard Method 4500-NO_3^-E). Nitrate was reduced to nitrite in a cadmium–

copper reduction column, and then, reacted with sulfanilamide to form a diazo compound. The absorbance was measured at 543 nm with a spectrophotometer (Hach DR3900, the USA). The results were expressed in mg/L NO_3^-.

- Chloride (Cl^-) was determined by argentometric titration (Standard Method 4500-Cl^-B). A known volume of sample was titrated with 0.0141 N $AgNO_3$ using potassium chromate indicator. The endpoint was indicated by the appearance of a persistent reddish-brown precipitate of silver chromate. Chloride concentrations were expressed in mg/L Cl^-.
- pH and Temperature were measured in situ immediately after sample collection using a calibrated multi-parameter probe (Hach HQ40d, the USA) to avoid changes due to storage. Calibration of the probe was performed daily with standard buffer solutions (pH 4.0, 7.0, and 10.0).

Data analysis

All collected data were processed and analyzed using Microsoft Excel and SPSS software. Descriptive statistical methods were applied to summarize the performance of the treatment plants. One-way analysis of variance (ANOVA) was used to examine significant differences in effluent quality among the sampled WWTPs. The results provide a comprehensive evaluation of hospital wastewater treatment efficiency, offering insights into the effectiveness of current management practices.

Results

Physicochemical characteristics of hospital wastewater

Table 1 presents a summary of the physicochemical characteristics of the hospital wastewater analyzed in this study. The measured values of COD, BOD_5, fecal coliform, and nitrate across various sampling events are depicted in Figures 1 to 4. The influent parameters were rigorously compared against national regulatory standards to accurately assess the levels of contamination and variability in wastewater composition.

pH

The pH values ranged from 6.2 to 9.04, with minor fluctuations. However, they remained largely within the acceptable standard limits of 6.5 to 8.5, indicating a near-neutral wastewater environment.

COD

The COD concentration varied significantly, ranging between 5 and 1625 mg/L, with a mean value of 106.8 ± 255 mg/L. In some instances, COD levels exceeded the permissible limit of 100 mg/L, suggesting substantial organic pollution.

BOD_5

The BOD_5 levels ranged from 2 to 630 mg/L, with an average value of 48.7 ± 124.5 mg/L, approaching the standard limit of 50 mg/L. This indicates varying degrees of biodegradability among the hospital wastewater samples.

Chloride

The chloride concentration varied between 0.2 and 809 mg/L, with a mean of 262 ± 29.7 mg/L. While within acceptable limits, fluctuations in chloride levels were observed, likely due to industrial or domestic discharges.

Nitrate

The nitrate concentration exceeded the standard limit of 10 mg/L in some samples, with an average of 18.9 ± 2.12 mg/L. This raises concerns regarding potential nutrient pollution.

TDS and TSS

The levels of TDS and TSS exhibited high variability, reaching maximum values of 3320 and 1400 mg/L, respectively. These findings suggest occasional heavy particulate matter and dissolved solid loads.

Turbidity

With an average value of 59.1 ± 97.4 NTU, turbidity frequently exceeded the standard limit of 50 NTU, indicating the presence of suspended materials that reduce water clarity.

Microbiological contamination of hospital wastewater

Microbiological analysis revealed high levels of contamination in hospital wastewater.

- Fecal coliforms: The mean concentration of fecal coliforms was 142 ± 355 MPN/100 mL, frequently exceeding the permissible limits.
- Total coliforms: The mean concentration of total coliforms was 292 ± 335 MPN/100 mL, surpassing safe limits and indicating significant microbial contamination.

These results emphasize the necessity for efficient wastewater treatment processes to mitigate organic matter, solid particles, and microbial contaminants before effluent discharge into the environment.

Effluent disposal pathways

Among the 59 hospital wastewater treatment plants

Table 1. Physicochemical characteristics of wastewater in this study

Parameter	Unit	Standard	Influent Range	Influent Mean ± SD
pH	Numeric	6.5–8.5	6.2–9.04	7.45 ± 0.1
COD	mg/L	100	5-1625	106.8 ± 255
BOD5	mg/L	50	2-630	48.7 ± 124.5
Chloride	mg/L	600	0.2-809	262 ± 29.7
Nitrate	mg/L	10	0.5-143.7	18.9 ± 2.12
TDS	mg/L	*	7–3320	879 ± 62.9
TSS	mg/L	*	3–1400	78.2 ± 452
Turbidity	NTU	50	0.09-2000	59.1 ± 97.4
Fecal Coliform	MPN/100 ml	400	> 3–1600 <	142 ± 355
Total coliforms	MPN/100 ml	1000	> 3–1600 <	292 ± 335

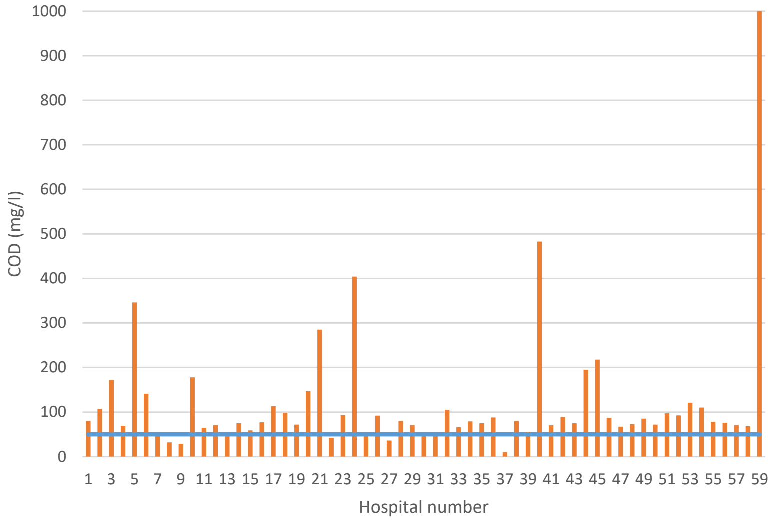

Figure 1. Chemical Oxygen Demand (COD) Variations Across Different Sampling Instances

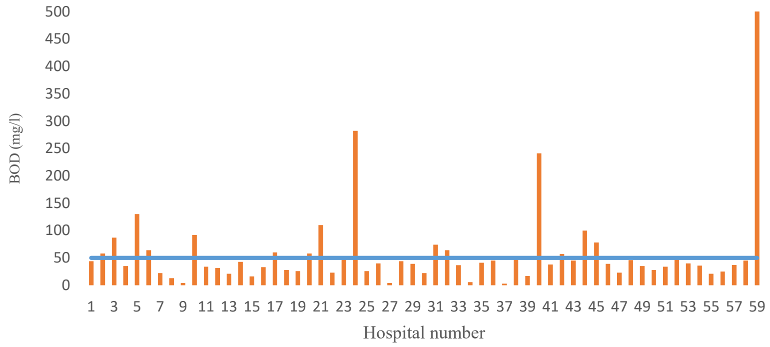

Figure 2. Biochemical Oxygen Demand (BOD) Variations Across Different Sampling Instances

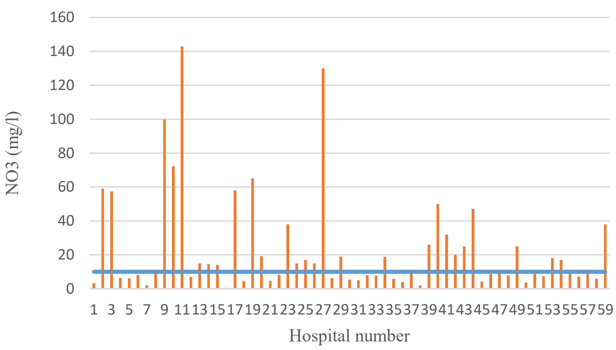

Figure 3. NO_3 Variations Across Different Sampling Instances

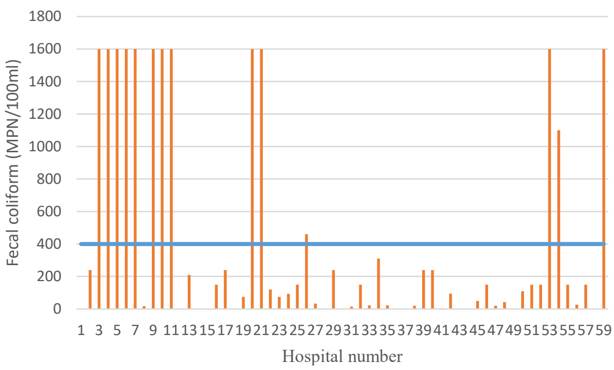

Figure 4. Fecal Coliform Variations Across Different Sampling Instances

analyzed in this study, the effluent disposal methods were categorized as follows:

- 66.6% of the treated effluent was discharged into the municipal wastewater system.
- 21.6% of the effluent was disposed of in infiltration wells.
- 11.6% of the effluent was used for irrigation of green spaces.

Compliance with environmental standards

Among the 13 hospitals that discharged effluent into infiltration wells, one hospital (7.69%) reported at least one instance per year where their wastewater's chemical or microbiological test results failed to meet the discharge standards set by the Iranian Environmental Protection Agency (IEPA).

Similarly, among the seven hospitals that utilized treated effluent for green space irrigation, two hospitals (28.5%) reported instances of non-compliance with IEPA discharge standards at least once per year.

Persistent Non-compliance with discharge regulations

Throughout the year, comprehensive chemical and microbiological assessments of hospital wastewater treatment plant effluents identified that five hospitals (8.33%) consistently exceeded regulatory limits in all collected samples.

These findings indicate persistent non-compliance with national discharge standards, highlighting the necessity for improved wastewater treatment strategies to ensure environmental safety and public health protection.

Discussion

Assessment of hospital wastewater treatment efficiency

The efficiency of hospital wastewater treatment systems is commonly evaluated using key physicochemical and microbiological parameters, including Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), nitrate concentration, and microbial contaminants. Elevated levels of these parameters in hospital effluents pose significant environmental and public health concerns, necessitating rigorous monitoring and optimization of treatment processes.

Organic pollution: BOD and COD levels

Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) are critical indicators of organic pollution in wastewater, reflecting both the biodegradability and potential toxicity of effluents. In this study, 23 out of 128 samples (17.9%) exhibited BOD and COD levels exceeding the permissible limits of 100 and 50 mg/L, respectively, as defined by the Department of Environment of Iran. These findings are consistent with the study conducted by Majumder et al. (2020), which reported average COD concentrations of 613 mg/L in Europe, 1074 mg/L in South America, and 591 mg/L in Asia. The observed variability in COD levels across different regions may be attributed to differences in hospital waste composition, treatment technologies, and regulatory enforcement. Moreover, Mesdaghinia et al. reported that BOD and COD concentrations in hospital wastewater in Tehran were comparable to those typically found in domestic wastewater, emphasizing the need for effective treatment strategies to mitigate organic pollution (33).

Among the hospitals evaluated in this study, 20 facilities utilized their treated effluent for disposal through infiltration wells and irrigation of green spaces. However, 4 out of these 20 hospitals (20%) failed to meet the discharge standards for COD and BOD, with concentrations exceeding the permissible limits. This highlights the necessity for improved treatment processes and strict adherence to regulatory guidelines. Failure to comply with these standards may result in excessive discharge of organic pollutants, posing significant risks to water quality and surrounding ecosystems.

Hospital wastewater typically contains elevated concentrations of pharmaceutical residues, detergents, and other organic compounds, contributing to high BOD and COD levels. Studies have demonstrated that conventional treatment methods, such as activated sludge and chlorination, may reduce these pollutants to some extent but are often insufficient for complete removal, particularly for complex organic compounds (5,33). Therefore, effective management of hospital wastewater requires continuous monitoring of BOD and COD, optimization of treatment processes, and, in many cases, the application of advanced technologies such as membrane bioreactors (MBRs), moving bed biofilm reactors (MBBRs), and advanced oxidation processes (AOPs) to ensure effluent quality complies with environmental standards (35).

In summary, the persistent exceedance of BOD and COD in hospital effluents underscores the importance of integrated strategies combining regulatory enforcement, technological advancements, and ongoing process optimization to mitigate organic pollution and protect aquatic ecosystems and public health.

Microbial contamination in hospital effluents

Hospital wastewater is a reservoir for a wide range of pathogenic microorganisms, including Escherichia coli (E. coli), Enterococci, thermotolerant coliforms, and fecal coliforms. In this study, 21 out of 128 samples (16.4%) exceeded the regulatory limits of 1000 MPN/100 mL for total coliforms and 400 MPN/100 mL for fecal coliforms. These findings are consistent with previous research indicating that conventional wastewater treatment systems may not adequately remove microbial contaminants, thereby increasing the risk of pathogen dissemination in the environment. For example, Exner et al. (2020) highlighted that hospital effluents often contain high loads of pathogenic bacteria and that insufficient treatment may contribute to environmental contamination and the spread of antibiotic-resistant bacteria (ARB).

Among the hospitals not connected to the municipal sewer system, 5 out of 20 facilities (25%) showed fecal coliform concentrations above the permissible limits. These results emphasize the necessity of implementing advanced disinfection strategies, including chlorination, UV irradiation, and high-efficiency filtration, to effectively reduce fecal coliform contamination. Strengthening wastewater treatment protocols in non-compliant hospitals is essential to mitigate public health risks and prevent the dissemination of microbial pollutants into the environment.

The exceedance of microbial contamination also underscores the potential role of hospital wastewater treatment plants (WWTPs) in facilitating the spread of ARB. The studies by Michael et al. (2013) and Zhang et al. (2020) demonstrated that inadequate disinfection and partial removal of ARB from effluents contribute to the horizontal transfer of resistance genes in aquatic ecosystems (20). Given these concerns, integrating advanced disinfection technologies such as UV irradiation, ozonation, and high-efficiency filtration could significantly improve pathogen removal and mitigate public health risks associated with hospital wastewater discharge.

Nitrate contamination and environmental implications

Another critical parameter in wastewater treatment efficiency assessment is nitrate concentration, as it serves as an indicator of nutrient pollution and potential eutrophication risks. In this study, 41 out of 128 samples (32.1%) had nitrate concentrations exceeding the standard limit of 10 mg/L, with an average effluent nitrate concentration of 18.9 mg/L. These findings suggest that conventional hospital wastewater treatment processes may be insufficient for effective nitrate reduction.

Among the hospitals surveyed that were not connected to the municipal sewer system, 7 out of 20 hospitals (35%) failed to comply with the Department of Environment's nitrate standards. This underscores the need for enhanced nitrogen removal strategies, including biological denitrification and ion exchange techniques, to minimize nitrate discharge and mitigate environmental risks.

Studies by Verlicchi et al. (2015) and Exner et al. (2020) have demonstrated that conventional hospital wastewater treatment processes are often insufficient for effective nitrate removal, which can lead to elevated nitrate concentrations in receiving water bodies and increase the risk of eutrophication. Given these concerns, the implementation of advanced nitrogen removal strategies, including biological denitrification, ion exchange, and other advanced treatment technologies, can significantly reduce nitrate levels and mitigate the environmental and public health risks associated with hospital wastewater discharge (35).

Sustainable management of hospital wastewater: a regulatory and technological perspective

Effective management of hospital wastewater demands a comprehensive and multi-faceted strategy that integrates stringent regulatory enforcement, technological advancements, and continuous environmental monitoring to reduce associated health and ecological risks. A key element in this strategy is the mandatory connection of all hospital wastewater treatment plants (WWTPs) to the municipal sewer system, ensuring systematic management of treated effluents, minimizing environmental pollution, and protecting local water resources. Centralized treatment through municipal wastewater infrastructure not only enhances operational efficiency but also facilitates adherence to established environmental standards and regulations.

Given the significant variability in hospital wastewater composition, ongoing monitoring and rigorous regulatory oversight are essential. The implementation of advanced online monitoring systems can improve compliance with both national and international discharge standards by enabling early detection of contaminants and optimizing treatment efficiency. Strengthening regulatory frameworks, including regular inspections and enforcement mechanisms such as penalties for non-compliance, remains critical to overcoming persistent challenges in hospital wastewater management.

A comprehensive review by Verlicchi et al. (2015), which analyzed 48 studies worldwide on hospital wastewater treatment, reveals that many existing systems are insufficiently effective, particularly in removing emerging contaminants like pharmaceutical compounds, disinfectants, and antibiotic-resistant bacteria. Conventional treatment methods, such as conventional activated sludge (CAS) and chlorination, often fall short in eliminating these pollutants. In contrast, advanced technologies—including membrane bioreactors (MBRs), advanced oxidation processes (AOPs), and activated carbon filtration (both powdered and granular)—demonstrate greater potential in reducing contaminant loads, especially during final treatment stages (35).

Furthermore, adopting cost-effective and sustainable treatment technologies is vital, especially in resource-limited settings. The integration of innovative and scalable solutions not only enhances wastewater management efficiency but also lowers operational costs, supporting long-term sustainability. According to the study by Verlicchi et al. (2015), several factors influence hospital wastewater treatment performance, including influent wastewater characteristics (pollutant concentrations), operational parameters (e.g., sludge concentration, sludge retention time, hydraulic retention time, pH, temperature, and chemical dosing), reactor type (conventional activated sludge versus membrane bioreactor), and environmental conditions (ambient temperature and light exposure). Additionally, sampling methods and frequency significantly impact evaluation outcomes. Therefore, due to the complex composition of hospital wastewater and variability in operational conditions, treatment performance requires careful and comprehensive assessment considering all these factors to achieve optimal results (35).

The inability of several WWTPs to consistently meet discharge standards can be attributed to operational deficiencies, including insufficient hydraulic retention time (HRT), low sludge retention time (SRT), aging equipment, lack of equalization tanks, and ineffective aeration or chlorination practices. Furthermore, the absence of advanced treatment stages, such as membrane filtration or ozonation, reduces the removal efficiency of persistent organic pollutants and microbial contaminants. Integration of hospital effluent into the municipal wastewater system may offer temporary dilution benefits, but this approach carries inherent risks. Hospital wastewater typically contains higher concentrations of pathogens, pharmaceutical residues, and disinfectants that may not be fully treated by conventional municipal treatment facilities, potentially contributing to the spread of antimicrobial resistance (AMR) and environmental contamination. Implementing hybrid treatment systems—combining biological processes with advanced disinfection technologies (e.g., chlorination + UV or ozonation)—can significantly enhance microbial reduction and pollutant removal. While initial investment costs may be higher, the long-term benefits of reduced health risks, regulatory compliance, and environmental protection make such solutions economically viable. In summary, a holistic approach combining robust regulatory frameworks, advanced treatment technologies, and continuous monitoring is essential to mitigate environmental contamination, ensure compliance with discharge standards, and protect public health.

Conclusion

This study demonstrates that, despite existing challenges in some hospital wastewater treatment plants (WWTPs), the implementation of proper primary treatment and strategic connection to municipal sewer systems can substantially improve effluent quality and reduce environmental and public health risks. The adoption of advanced hybrid technologies, including membrane bioreactors (MBRs), moving bed biofilm reactors (MBBRs), advanced oxidation processes (AOPs), and modern disinfection methods such as ultraviolet (UV) irradiation and ozonation, enhances the removal of chemical and microbial contaminants, facilitating compliance with the national and international discharge standards. Continuous monitoring, process optimization, and strengthening of regulatory frameworks ensure that hospital wastewater management not only meets compliance requirements but also evolves into a sustainable and efficient system that safeguards community health and aquatic ecosystems. Consequently, adopting a comprehensive and integrated approach to hospital wastewater management provides significant opportunities to reduce pollutant emissions, control antibiotic-resistant bacteria, and enhance environmental quality, thereby offering a clear pathway toward sustainable wastewater management and public health protection.

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Authors' Contribution

Conceptualization: Maryam Meserghani, Pezhman Gheitasian, Elham Shariatmadari, and Farbod Ebadifard Azar.
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Formal analysis: Maryam Meserghani and Pezhman Gheitasian.
Funding acquisition: Maryam Meserghani and Pezhman Gheitasian.
Investigation: Maryam Meserghani and Pezhman Gheitasian.
Methodology: Maryam Meserghani and Pezhman Gheitasian.
Project administration: Maryam Meserghani and Pezhman Gheitasian.
Resources: Maryam Meserghani and Pezhman Gheitasian.
Software: Maryam Meserghani and Elham Shariatmadari.
Supervision: Maryam Meserghani and Pezhman Gheitasian.
Validation: Maryam Meserghani, Pezhman Gheitasian, and Farbod Ebadifard Azar.
Visualization: Maryam Meserghani and Pezhman Gheitasian.
Writing–original draft: Maryam Meserghani and Pezhman Gheitasian.
Writing–review & editing: Maryam Meserghani and Pezhman Gheitasian.

Competing Interests

The authors declare that there is no conflict of interests.

Ethical Approval

This study was approved by the Ethics Committee of the Iran University of Medical Sciences (Ethical code: IR.IUMS.REC.1402.430). The authors affirm that all the data collected during the study are accurately presented in the manuscript, and no information from this study has been or will be published independently elsewhere.

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