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Assessing Hospital Wastewater in High-Altitude Himalayan District: Physico-chemical Insights and Environmental Risks

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KEYWORDS

Hospital wastewater, Physico-chemical characteristics, Sewage treatment plant, Environmental implications, Biodegradability Index (BOD_5/COD), Water quality monitoring, Pollutant load reduction.

ABSTRACT:

Hospitals are facilities that require a large amount of water of a specific quality and in hygienic conditions continuously. However, providing hospitals with enough water, both in terms of quality and quantity, has become a significant expense in communities where the water supply is challenging and the water quality is poor. In addition, the structure of hospital wastewater contains a large number of macro and micro-contaminants. These contaminants have significant detrimental effects on both terrestrial and aquatic ecosystems. As a result, hospitals are now required to install and run integrated water and wastewater management systems within the framework of the sustainability concept. The present study investigated the physico-chemical characteristics and environmental implications of hospital wastewater from the Government Hospital, Keylong, Himachal Pradesh, where effluents are treated in an on-site sewage treatment plant (STP) before discharge into a nearby river. Wastewater samples were collected at both influent and effluent points, and analyzed for key parameters including pH, temperature, conductivity, turbidity, TSS, TDS, hardness, COD, BOD, chloride, sulfate, calcium, and magnesium using APHA standard methods. The Biodegradability Index (BOD_5/COD ratio) was also calculated. Results indicated that raw effluents exhibited elevated BOD (428 mg/L), COD (1192 mg/L), turbidity (173.5 NTU), TDS (4554.4 mg/L), hardness (361.3 mg/L), chloride (1397 mg/L), calcium (276 mg/L), and magnesium (100.5 mg/L), with several parameters exceeding CPCB permissible limits. Treated and downstream samples, however, generally complied with standards, reflecting effective reduction in organic and inorganic pollutant loads. The Biodegradability Index decreased from 0.33 in the influent to 0.10 in treated the effluent, indicating lower biodegradability after treatment. Stable pH (6.44–8.24) and temperature (21.3–22.0 °C) suggested favourable microbial activity and minimal thermal pollution risks. Nonetheless, high ionic loads, fluctuating chloride, and sulfate values highlight sporadic discharges and the potential for ecological stress. In conclusion, while the STP achieved substantial pollutant reduction, persistent exceedances in raw influent emphasize the need for stricter source control, advanced treatment integration, and continuous monitoring to safeguard aquatic ecosystems and public health in fragile Himalayan environments.

1. Introduction

Hospital wastewater generation has increased dramatically in recent decades as healthcare services and medicinal products have advanced [1]. The quantity and composition of hospital wastewater are influenced by a variety of elements, including water supply, the number of hospital beds, facilities such as air conditioning, kitchens, and laundries, the types and sizes of wards or units, and overall management practices. These factors contribute to the overall wastewater discharge [2]. Hospital wastewater is a complex mixture that includes not only pharmaceuticals and their by-products, but also disinfectants, diagnostic chemicals, and other substances from laboratories, research activities, diagnostic procedures, and patient excretions [3,4].

Hospital effluents often have greater amounts of nitrogen, ammonia, chemical oxygen demand (COD), and biochemical oxygen demand (BOD) than do domestic sewage [5,6]. Additionally, it is not as biodegradable as municipal wastewater, which makes it challenging to treat with traditional biological systems [7]. According to reports, hospital effluents are 5–15 times more harmful than municipal wastewater due to their composition [8]. In addition, hospital discharges contain a wide variety of microorganisms, such as parasites, fungi, viruses, and bacteria. The growth of susceptible strains is suppressed, and the propagation of resistant populations in receiving water bodies is encouraged by the notable presence of numerous antibiotic-resistant bacteria in hospital wastewater [9]. In order to detect faecal pollution, routine monitoring typically uses indicator species because measuring microbial populations in water samples is expensive and analytically challenging. A member of the faecal coliform group, Escherichia coli is one of the most commonly utilized indicators [10]. Gram-negative Escherichia coli bacteria are distinguished by their rounded ends. Although they also inhabit secondary environments like water, sediments, and soils at various points of their life cycle, their major home is the intestinal tract of warm-blooded animals [11-14]. As a result, the finding of E. coli in drinking water is frequently known as the "coliform index" and is widely accepted as a sign of faecal contamination [15]. In natural environments, a variety of biotic and abiotic factors affect E. coli's ability to survive and grow. In contrast to biotic variables, which include the presence of competing microorganisms, resource use, competition for ecological niches, and the capacity of E. coli to build biofilms, abiotic factors include temperature, the availability of nutrients and water, pH levels, and sun radiation [16]. Numerous settings, such as wastewater, soils, aquatic systems, plants, fruits, vegetables, raw meat, and unpasteurized milk, can support the survival of these bacteria [12]. While E. coli strains are typically thought of as commensals in the stomach, they can also cause a variety of intestinal and extra intestinal diseases, such as colibacillosis in poultry and septicemia, meningitis, and urinary tract infections in humans [12]. Hospital wastewater is frequently dumped straight into city sewage systems in many developing countries, and then untreated, into natural water bodies [17-19]. According to research, the activated sludge process in treatment facilities may suffer if hospital wastewater and municipal sewage are combined [8]. Accordingly, it is thought to be essential to treat hospital wastewater separately in order to reduce the danger of contamination that comes with combining these effluents [20]. Functionalized membrane filtration, heterogeneous photo catalysis, persulfate-based degradation, Fenton-like oxidation, and adsorption techniques are among the advanced treatment approaches that have been investigated for the elimination of pollutants originating from hospitals [21]. Conventional wastewater treatment systems are quite poor in eliminating pharmaceutical residues [22-24], despite being generally successful at treating sewage [25]. Furthermore, these procedures are frequently quite expensive and energy-intensive, which prevents them from being widely used in developing nations [26,27]. According to scholars, effective treatment solutions usually include integrating two or more technologies in an integrated strategy, as no single treatment technology can effectively address all contaminants across varied wastewater sources [28].

2. Study Area

The Government Hospital is the main medical facility for the dispersed and mountainous population of Keylong, Himachal Pradesh, (about 32.5708°N, 77.0317°E; elevation 3,080 meters above sea level). It is located in Lower Keylong Village, close to the Government Senior Secondary School [29]. A sewage treatment plant (STP) on the hospital grounds treats hospital wastewater before it is released downstream into a neighbouring river. For research on the quality and environmental impact of hospital wastewater in a remote and high-altitude Himalayan district, this particular geographical and infrastructure context, along with the presence of an STP and the discharge of treated effluent into the river, offers a representative and instructive setting.

3. Methods

Wastewater sampling

Samples of wastewater were gathered in 1000 mL bottles that had been washed and sterilized beforehand. They were then kept at 4 °C until they were taken to the Himachal Pradesh Pollution Control Board Regional Laboratory for examination. Sampling was done at the STP's intake and output between 9:00 am and 5:00 pm, when hospital activity was at its highest. Analyses in the lab were started right away, and all samples were kept at 4 °C. Following standard procedures, the following physico-chemical parameters were evaluated: temperature, pH, conductivity, turbidity, total suspended solids (TSS), total dissolved solids (TDS), total hardness, chemical oxygen demand (COD), biological oxygen demand (BOD), chlorine, sulfate, calcium, and magnesium [30].

Physico-chemical analysis of wastewater

The Standard Methods for the Examination of Water and Wastewater [30], were followed in every analysis unless otherwise noted. A Hanna HI98129 Combo Meter, a portable tester, was used to assess temperature, pH, and electrical conductivity (EC), in situ [31]. Using a turbidity meter (HANNA, HI 93703-11) and the nephelometric approach, turbidity was measured [32]. The gravimetric method was used to determine the total suspended solids (TSS) and TDS [33]. Utilizing the EDTA titrimetric method (APHA 2340 C), total hardness—which can be caused by pharmaceutical formulations, laboratory chemicals, and sterilization by-products in hospital wastewater—was measured. The Reflux Digestion Method (APHA 5220 C) was used to assess the chemical oxygen demand (COD) [33], and the WTW OxiTop® system was used to calculate the biochemical oxygen demand (BOD_5) in compliance with the manufacturer's protocol [34]. The argentometric titration method (APHA 4500-Cl^- B) was used to measure the concentration of chloride. The barium sulfate turbidimetric method (APHA 4500-SO_4^{2-} E) was used to quantify sulfate. Using the EDTA titrimetric method (APHA 3500-Ca B), the calcium content was ascertained. According to APHA 3500-Mg B, magnesium was computed as the difference between total hardness and calcium hardness.

Biodegradability Index

The biodegradability of hospital wastewater was assessed using the BOD_5/COD ratio, commonly referred to as the Biodegradability Index (BI) [35]. According to the findings of this study, the BI for raw effluent was

approximately 0.33, while it decreased to 0.10 for treated effluent and 0.09 for downstream samples. These values indicate that the raw influent exhibited moderate biodegradability, whereas the treated and downstream effluents showed comparatively lower biodegradability.

4. Results and Discussion

Physicochemical characterization

The physicochemical assessment of hospital wastewater involves the measurement of multiple key parameters [36]. Findings from the present study indicated that values of BOD (raw), COD (raw), TDS (raw), and turbidity exceeded the permissible limits prescribed by CPCB for safe discharge into the environment. Among these parameters, pH plays a particularly vital role as it governs most chemical reactions occurring in aquatic systems. It serves as an indicator of water's acidity or alkalinity, with extreme values posing risks to aquatic organisms. Even minor fluctuations in pH can significantly affect aquatic biota, while certain pH ranges may intensify heavy metal toxicity.

Consequently, pH is considered a fundamental determinant of water and wastewater quality [28,37]. In the present investigation, pH values ranged between 6.44 and 8.24, with an average of 7.18 ± 0.74. The results indicate that the pH of the treated effluent was slightly higher compared to the raw influent, which may be attributed to the release of ammonia gas during the anaerobic degradation of organic nitrogen [38]. Moreover, photosynthetic activity by aquatic plants can also elevate pH levels by removing carbon dioxide from the water [39]. Despite minor variations, the pH of both influent and effluent remained within the CPCB permissible range of 6.5-8.5, which supports favorable conditions for aerobic microbial processes in wastewater treatment [40].

In this study, wastewater temperature ranged narrowly from 21.3 to 22.0°C, with an average of 21.63° 0.29°C, which is well below the CPCB permissible limit of 40°C. Such stable and relatively low values indicate minimal risk of thermal pollution. Temperature plays a vital role in regulating several water quality processes, including solubility of gases, chemical reactivity, and microbial activity [41]. Elevated temperatures typically reduce dissolved oxygen concentrations, increasing stress on aquatic organisms [42,43]. However, in this case, the observed values are favorable, suggesting that the wastewater poses little thermal stress to aquatic biota and is unlikely to impair biological treatment efficiency [44].

Figure 1: Comparison of Physico-chemical Parameters in Wastewater.

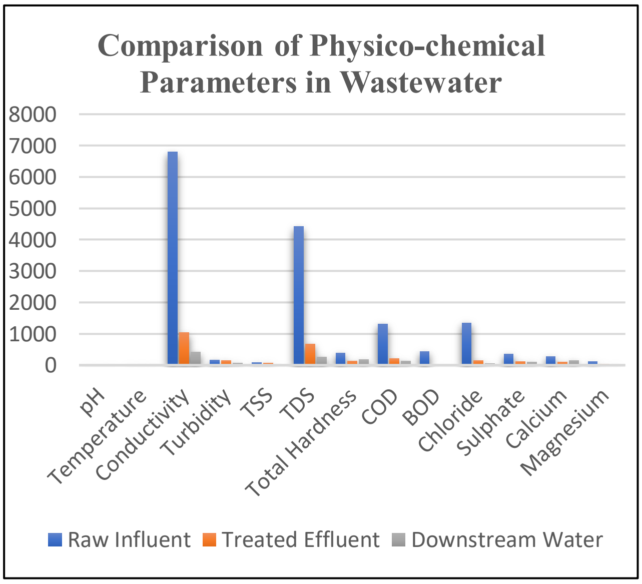


Table 1: Physico-chemical Parameters of Hospital Wastewater.

Parameter	Units	CPCB Standard	Range	Mean	Mean ± SD
pH	–	6.5–8.5	1.8	7.18	7.18 ± 0.74
Temperature	°C	≤40°C	0.7	21.63	21.63 ± 0.29
Conductivity	µS/cm	–	6383.9	2748.37	2748.37 ± 2742.12
Turbidity	NTU	≤10	92.8	127.07	127.07 ± 38.48
TSS	mg/L	≤100	70.0	56.68	56.68 ± 29.66
TDS	mg/L	≤2100	4149.54	1786.44	1786.44 ± 1745.69
Total Hardness	mg/L	≤300	264	229.33	229.33 ± 90.82
COD	mg/L	≤250	1192	552.0	552.0 ± 544.06
BOD	mg/L	≤30	428	157.33	157.33 ± 199.92
Chloride	mg/L	≤1000	1302	517.0	517.0 ± 551.21
Sulphate	mg/L	≤400	252.39	189.57	189.57 ± 108.09
Calcium	mg/L	≤200	184	176.0	176.0 ± 75.20
Magnesium	mg/L	≤100	84	53.33	53.33 ± 38.56

Water's electrical conductivity (EC), which is primarily influenced by its ionic strength, dissolved ion concentration, and measurement temperature, is a measure of its capacity to transport an electric current [45]. It is a reliable indicator of salinity, or the total quantity of dissolved salt in water, [46]. From 638.9 to 7022.8 ∝S/cm, the EC values in our study varied significantly, with an average of 2748.37 ± 2742.12 ∝S/cm. These significant differences suggest high ionic loads in the effluent, even though the CPCB has not set a precise EC norm. These high values may be due to the degradation of organic contaminants into simpler ionic forms or to the release of nutrients during the decomposition of plant matter, which raises dissolved ion concentrations [39].

Turbidity, a metric for water transparency, indicates the amount of light that may flow through the water column [47,48]. It is brought on by the existence of suspended particles that absorb and scatter infrared and visible light. These particles can range in size from larger aggregates to extremely tiny colloidal molecules [49]. The health of aquatic ecosystems and primary productivity are hampered by high turbidity because it limits the amount of light that photosynthetic organisms can access [50]. With an average of 127.07 ± 38.48 NTU and recorded values ranging from 80.7 to 173.5 NTU, the turbidity levels in the current investigation were consistently higher than the CPCB standard of δ10 NTU.

One of the main pollutants causing the decline in water quality is total suspended solids (TSS) [51]. Increased concentrations limit aquatic species' ability to breathe, impede oxygen exchange between air and water, and cause turbidity, which lowers the amount of dissolved oxygen available. Additionally, they prevent light from penetrating the water column, which inhibits the photosynthetic activity of algae and aquatic plants. Additionally, suspended

particles' direct absorption of solar radiation can increase water temperature and decrease oxygen solubility [52]. Lower flow velocity across the treatment substrate facilitates the sedimentation, filtration, flocculation, and aggregation processes that are commonly used in sewage treatment plants (STPs) to remove TSS [53]. In the present study, TSS concentrations ranged from 22.2 to 92.2 mg/L, with an average of 56.68 ± 29.66 mg/L. These values were consistently within the CPCB permissible limit of δ100 mg/L, though moderate variability across samples was evident.

The combined concentration of organic and inorganic materials in water that are dissolved, ionized, or colloidal is known as total dissolved solids, or TDS. In addition to residues of organic substances, these solids usually consist of calcium, magnesium, sodium, potassium, bicarbonates, chlorides, and sulfates [54]. In addition to limiting the water's appropriateness for drinking, irrigation, and industrial use, elevated TDS can affect water density, decrease gas solubility (especially oxygen), and interfere with aquatic species' osmoregulation [37]. TDS concentrations in the current investigation ranged widely, from 404.9 to 4554.4 mg/L, with an average of 1786.44 ± 1745.69 mg/L. The CPCB permitted limit of δ2100 mg/L was exceeded by raw effluent samples, but processed and downstream samples stayed in compliance.

The concentration of divalent cations, mainly calcium (Ca^{2+}) and magnesium (Mg^{2+}), which come from the geochemical formations that water interacts with, is measured by water hardness. Polyvalent ions, including iron, barium, manganese, and strontium, may also contribute [55,56]. Bicarbonates and carbonates of Ca^{2+} and Mg^{2+} can provide carbonate (temporary) hardness, while chlorides, sulfates, and nitrates of these and other cations can produce non-carbonate (permanent) hardness. Total hardness is referred to as non-carbonate hardness when it surpasses the sum of carbonate and bicarbonate alkalinity, and as totally carbonate hardness if it is equal to or less [56]. Hardness levels in the current study averaged 229.33 ± 90.82 mg/L, with a range of 97.3 to 361.3 mg/L. While processed and downstream waters met allowable values, only raw effluent samples showed excesses over the CPCB threshold of 300 mg/L.

The quantity of oxygen used when strong oxidizing agents like dichromate and permanganate chemically oxidize organic and inorganic materials is measured by the Chemical Oxygen Demand (COD) [57]. It indicates that there are reducing agents in the water, mostly organic materials, but also ferrous salts, nitrites, and sulfides. High COD levels signify low microbial activity that inhibits the biodegradation of organic pollutants and significant oxygen depletion, which can harm aquatic life [44,58]. The average COD value in this study was 552.0 ± 544.06 mg/L, with a range of 128 to 1320 mg/L. While processed and downstream samples showed notable decreases, nearly reaching compliance, raw effluent tests showed a large organic load, exceeding the CPCB permitted limit of 250 mg/L.

The amount of dissolved oxygen needed by aerobic bacteria to break down organic matter in water at a certain temperature and incubation time, usually five days, is known as the Biochemical Oxygen Demand over Five Days (BOD_5) [54,59,60]. In aquatic systems, it acts as an indirect indication of chemical and biodegradable organic contaminants [61]. Elevated BOD_5 levels are linked to increased oxygen depletion, which strains aquatic creatures and causes asphyxia and death [62]. Physical processes such as sedimentation, filtration, and predation on particulate matter, as well as microbial decomposition of organics, might cause declines in BOD$_5$ after treatment [63]. In this study, BOD values ranged from 12 to 440 mg/L, with a mean of 157.33 ± 199.92 mg/L. Raw effluent exceeded the CPCB permissible limit of δ30 mg/L, whereas treated and downstream samples complied with the standard, reflecting effective reduction of biodegradable organic load during treatment.

The persistence and pervasiveness of chloride contamination in aquatic systems have made it a major environmental concern. Industrial discharges are the main source, especially from activities that usually generate chloride-rich effluents, like metal smelting, flue gas desulfurization, and inland seawater desalination [64-66]. Chloride is extremely soluble in water and can change into metal chlorides, oxychlorides, or layered double hydroxide (LDH) precipitates when metal-based precipitants are present [67]. Chloride concentrations in the current study had a mean of 517.0 ± 551.21 mg/L, with a range of 95 to 1397 mg/L. The CPCB allowed limit of 1000 mg/L was exceeded by raw effluent samples, whereas processed and downstream samples stayed within compliance. The observed decrease in chloride levels following treatment suggests efficient removal mechanisms, most likely via the treatment system's adsorption, dilution, and precipitation processes. To avoid ecological hazards like salinization and ion toxicity in freshwater environments, however, the significant variation in chloride concentrations points to sporadic high-load discharges, calling for tighter source-control regulations and ongoing monitoring.

One of the most important components of wastewater sludge is sulfur, which can produce sulfur oxides (SOx) when it burns, which contributes to acid rain and air pollution [68,69]. This is especially true when the sludge is used for combustion or co-combustion with other fuels. Both inorganic (such as sulfates and metal sulfides) and organic (such as ester- or carbon-bonded compounds) forms of sulfur can be found in wastewater [69]. By converting sulfate (SO_4^{2-}) into sulfides (H_2S, HS^-, S^{2-}) and competing with methanogens and homoacetogens for shared substrates in digesters, sulfate-reducing bacteria (SRB) are essential to the sulfur cycle under anaerobic circumstances [70]. The mean sulfate content in the current study was 189.57 ± 108.09 mg/L, with a range of 63 to 315.4 mg/L. The fact that all measured values stayed within the 400 mg/L CPCB allowed limit indicates that sulfate contamination in the effluents under sample does not currently provide a compliance concern. Nonetheless, the comparatively large range of values suggests that inputs are changing, perhaps as a result of changes in microbial activity or industrial emissions. Since high sulfate levels can promote excessive SRB activity and result in hydrogen sulfide generation, which increases the risk of toxicity, corrosion, and odor nuisance in aquatic settings, it is advised to conduct continuous monitoring.

In aquatic ecosystems, calcium and magnesium are vital cations that are crucial for buffering capacity, hardness, and biogeochemical cycles [71]. Although both ions are essential for aquatic environments, high quantities can degrade water quality and affect whether it is suitable for residential and commercial use. Excessive amounts of magnesium can raise soil alkalinity and lower crop output, making it a crucial metric for irrigation water quality [72]. The calcium values in this study had a mean of 176.0 ± 75.20 mg/L, with a range of 92 to 276 mg/L. While processed and downstream samples comply with the CPCB allowed limit of 200 mg/L, raw effluent samples surpassed it. The mean magnesium concentration was 53.33 ± 38.56 mg/L, with a range of 16.5 to 100.5

mg/L. Only raw sewage tests showed levels above the CPCB threshold of 100 mg/L.

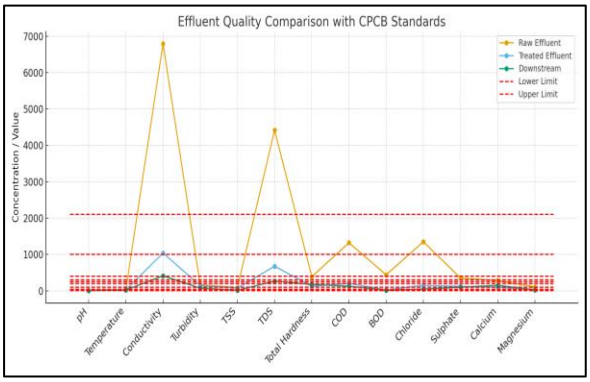
Environmental Implications of Hospital Wastewater

The results of this study show that hospital wastewater is a complicated mixture of microbiological, organic, and inorganic contaminants that has a big impact on wastewater management systems, aquatic ecosystems, and public health. Increased BOD and COD levels are a reflection of the high organic load in untreated wastewater, which can cause receiving water bodies to lose dissolved oxygen and create hypoxic conditions that are harmful to aquatic life. Because TSS and high turbidity block light penetration, photosynthesis in aquatic plants and algae is limited, which lowers primary productivity and upsets the food web. Additionally, a buildup of suspended particulates can suffocate benthic ecosystems and reduce aquatic species' ability to breathe. Excessive TDS and electrical conductivity levels are indicative of significant ionic pollution, which can change aquatic species' osmotic balance, cause soil to become salinized over time when used for irrigation, and jeopardize the usage of water in homes and businesses.

Changes in metal solubility, ion toxicity, and salinization are ecological hazards associated with the detected chloride contamination that could set off secondary pollution pathways. In a similar vein, the varying sulfate levels draw attention to the possibility of anaerobic hydrogen sulfide production, which is linked to toxicity, odor nuisance, and corrosion of infrastructure. In addition to making water less suitable for irrigation, high quantities of calcium and magnesium, which contribute to hardness, can also affect crop production and soil structure. Parallel to this, aquatic biodiversity is threatened by high BOD and COD loads, and ecological stress can be exacerbated by minor pH fluctuations that increase the toxicity of heavy metals and other contaminants.

There was little chance of thermal pollution in this investigation because of the ideal thermal conditions. But what's more concerning are the synergistic interactions between several contaminants. For instance, excessive levels of hardness, TDS, and chloride not only degrade water quality but also complicate biological treatment processes, necessitating sophisticated treatment measures. Thus, untreated or inadequately treated hospital wastewater can serve as a continuous source of pathogen growth, eco-toxicological stress, and the spread of emergent contaminants (such as medications, antibiotic residues, and disinfectants that are missed by standard physicochemical analyses). When taken as a whole, these effects highlight how urgently strict effluent management, active monitoring, and the use of cutting-edge treatment technologies are needed to reduce hospital wastewater's environmental impact before it reaches natural ecosystems.

Figure 2: Effluent Quality Comparison with CPCB Standards.



5. Conclusion

The physicochemical assessment of hospital wastewater revealed significant variability across key parameters, with several exceeding CPCB permissible limits in raw effluents, notably BOD, COD, turbidity, TDS, hardness, calcium, magnesium, and chloride. These findings highlight the presence of high organic and inorganic pollutant loads before treatment, posing potential risks to aquatic ecosystems through oxygen depletion, salinization, and metal toxicity. However, post-treatment and downstream samples generally complied with CPCB standards for most parameters, demonstrating the effectiveness of the treatment process in improving effluent quality. Stable pH and temperature values within acceptable ranges further indicate favourable conditions for microbial activity and reduced thermal stress. Elevated electrical conductivity and fluctuating sulfate and chloride levels suggest periodic high-load discharges and the influence of both natural and anthropogenic inputs, underscoring the need for continuous monitoring. Overall, while treatment systems achieved substantial pollutant reduction, persistent exceedances in raw wastewater emphasize the necessity for stricter source-control measures, optimized treatment processes, and integrated management strategies to mitigate hospital wastewater's environmental impacts.

Conflict of interest: The authors have no conflict of interest.

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