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Wastewater System Efficacy and Environmental Impact: Hawassa Referral Hospital, Ethiopia

Musema Shewaga Bekei[1]; Semaria Moga Lencha[2*]; Abreham Birhane Kassay[2] and Daniel Fitamo[3]

[1]*Department of Natural Resource Management, College of Agriculture, Wolkite University, Wolkite, Ethiopia.*

[2]*Department of Water Resources and Irrigation Engineering, Institute of Technology, Hawassa University, Hawassa, Ethiopia.*

[3]*Departments of Biology, College of Natural and Computational Science, Hawassa University, Hawassa, Ethiopia*

Corresponding Author: Semaria Moga Lencha (smrlencha03@gmail.com)

Abstract

Hospitals generate significant amounts of infectious and hazardous wastewater, making effective treatment essential. This study aimed to evaluate the characteristics of sewage produced by Hawassa Referral Hospital, the effectiveness of its treatment process, and the potential environmental contamination. Sampling was conducted periodically (March to October 2024) from 11 locations. Both sampling and analysis were performed using standard methods. Statistical analysis, mean, standard deviation, and a correlation matrix were prepared using physicochemical parameters. The mean concentration of BOD_5 *(188.6mg/L), COD (485.5mg/L), TSS (282.9mg/L), EC (312.7µS* cm^{-1}*),* PO_4^{-3} *(18.63 mg/L),* NO_3^-*(18.7mg/L) and turbidity (153.2 NTU) were higher than the maximum permissible level of effluent discharged to lake water while TDS (494mg/L) and* SO_4^{-2} *(37.3mg/L) were below the limit. The concentration of all heavy metals, except* Cr^{+6}*,* Zn^{+2}*, and* Hg^{+2}*, was higher than the Maximum Contaminant Level (MCL). The level of all parameters except (*Hg^{+2}*,* Pb^{+2}*,* $Cd^{+2,}$ *and* Ni^{+2}*) had a significant (*$P < 0.05$*) difference between each sampling spot. Likewise, the average Total coliform (TC) and Faecal coliform (FC) were greater than the effluent standard discharged to the lake. As for the performance of each unit of Ponds, Facultative Ponds had good performance on downsizing FC, TC, BOD, TSS, TDS, and* Fe^{+3} *than other ponds. Alternatively, Maturation Ponds had better performance in dropping of* SO_4^{-2} *and TKN than other Ponds. Likewise, Fish Pond exhibited good reduction of COD and* PO_4^{3-}*. Conversely, Fish Ponds performed poorly in reducing FC,* Fe^{+3}*,* $Mn^{+2,}$ *and* Zn^{+2}*. Evidently, the Waste Stabilization Ponds (WSPs) were inefficient in treating wastewater, primarily due to poor physical and process design, inadequate waste management practices (identification, sorting, and disposal), and insufficient* *operation and maintenance. The elevated levels of most of the pollutants in samples from the Littoral Zones of Hawassa Lake suggest a potential environmental risk in this area, particularly along the discharge route.*

***Keywords*:** Hospital Wastewater; Lake Hawassa; Local Contamination; Waste Stabilization Ponds; Wastewater Treatment.

1. Introduction

Hospitals, medical centres, laboratories, veterinary clinics, research centres, morgues, blood banks, and nursing homes generate most healthcare waste (HCW). High-income countries generate up to almost 11 kg of hazardous waste per bed per day, while low-income countries generate up to 6 kg. In low-income countries, HCW is often not separated into hazardous and non-hazardous waste (Miamiliotis & Talias, 2023; Taslimi et al., 2020).

HCW poses significant risks to health and the environment due to the presence of medical, biomedical, and clinical waste from health care facilities, and can be hazardous chemicals, pharmaceuticals, infectious or non-infectious, or chemical (Amin et al., 2024; Noman et al., 2021; Yazie et al., 2019). It includes laboratory and pathology waste, body fluids, and sharps (Awodele et al., 2016). Moreover, untreated liquid hospital waste contains chemicals and pharmaceuticals such as drug residues, disinfectants, and antineoplastic drugs (Thakur et al., 2023).

It is approximately 1-2% of the total municipal waste stream 85% of HCW is non-hazardous, but the remaining 15% is hazardous (Aziz et al., 2022; Janik-Karpinska et al., 2023). Besides, HCW containing resistant bacteria can suppress the growth of susceptible bacteria, potentially increasing the prevalence of antibiotic-resistant bacteria in water bodies where the wastewater is released. When antibiotic-resistant bacteria are discharged into the environment, they can serve as reservoirs for antibiotic resistance genes, posing a risk to public health (Asfaw et al., 2017). Moreover, the absence of targeted treatment methods for hospital wastewater has contributed to higher concentrations of gastroenteric viruses in aquatic environments (Amin et al., 2024).

In developing countries like Ethiopia, wastewater management faces additional challenges. For instance, Getahun et al. (2012) noted the inefficiencies of treatment systems in urban areas, often resulting in the discharge of untreated or poorly treated wastewater. In a similar vein, research by Ortúzar et al.(2022) identified the presence of pharmaceutical residues and microbial contaminants in water bodies near healthcare facilities, highlighting the need for improved wastewater treatment practices.

In developing countries hospital effluents are often discharged into municipal sewer systems and into receiving waters without any treatment to reduce public health risks (Karungamye et al., 2023). Udofia, (2016) found that healthcare waste in Africa is often poorly managed, with some facilities discharging untreated waste into municipal sewers, posing public health and environmental risks. This makes it necessary to consider separate treatment of hospital wastewater to avoid contamination that may occur when hospital wastewater is mixed with municipal wastewater (Karungamye et al., 2023). Awodele et al. (2016) state that some hospitals recycle, while others mix infectious waste with municipal waste and discharge it into sewers. The lack of uniform national guidelines is contributing to inconsistent practices. Ghana, Lesotho, and Eritrea lack consistent guidelines. Nigeria, Gambia, and Kenya are legally obliged to reduce POPs, including those from HCW incineration. However, implementation lags due to inadequate infrastructure, funding, and enforcement (Awodele et al., 2016; Karungamye et al., 2023).

The removal of pollutants, coarse particles, toxins and potential pathogens is the primary objective of wastewater treatment (J. A. Silva, 2023). However, in some cases, hospital effluent often flows directly into nearby water bodies due to lack of investment and infrastructure (Onu et al., 2023). Lencha et al, (2021) found that the referral hospital was discharging effluent directly into Lake Hawassa, which was a threat to people and marine life.

Lake Hawassa, a vital ecological and economic resource for the region, is situated in close proximity to the hospital and is potentially at risk of contamination from the hospital's wastewater. The lake supports local livelihoods through fishing, agriculture and tourism. However, the discharge of poorly treated hospital wastewater containing pathogens, pharmaceuticals and chemical residues poses a significant threat to the lake's water quality, aquatic ecosystems and public health. Contamination of the lake could lead to the spread of waterborne diseases, disruption of aquatic life, and long-term environmental degradation (Daka et al., 2021).

Hawassa Referral Hospital, located in the city of Hawassa, was built on the southwestern shore of the Lake.is a critical healthcare facility serving a large population in the Sidama Regional state and beyond. Like many healthcare facilities, it generates significant amounts of medical and domestic waste (143.3 $m^3 day^{-1}$ wastewater) which must be managed effectively to prevent environmental contamination and public health risks. Hawassa Referral Hospital uses WSPs as one of its primary methods of treating wastewater, generates sizable effluent (139.61 m^3/day) that is bound to be discharged into Lake Hawassa are designed to treat organics and pathogens through natural biological processes. While WSPs are cost-effective and widely used in low-resource settings, their performance is often compromised due to design flaws, operational inefficiencies, and overloading, which can result in the discharge of inadequately treated effluent into the environment. Therefore, the performance of these ponds is critical to ensuring that the treated effluent does not pose a risk to the environment, particularly Lake Hawassa, which is located in close proximity to the hospital.

Despite the lack of studies on hospital wastewater treatment and disposal in Ethiopia and the study area, there is very little information on the subject. It is therefore essential that relevant studies are undertaken to address the lack of information. This study is therefore aimed to provide data on the type of wastewater Generated, Its Treatment, Potential Contamination of the Lake Hawassa and Suggest Mitigation Measures.

2. Materials and Methods

2.1. Study Area

Hawassa City Is One Of Rapidly Developing Urban Center In Ethiopia And It Is The Capital Of Sidama Regional State Of The Country. The Geographical Location of the City Lies between the Latitude 765,000 To 785,000N And Longitude of 432,000 to 452,000E adjacent to the shoreline of Lake Hawassa. The city is situated in a region that experiences a tropical highland climate, characterized by distinct wet and dry seasons. The computed mean annual rainfall is 975 mm with significant interannual variability. The monthly average temperature varies between 10°C to 30°C. Hawassa Referral Hospital (HRH) is a prominent teaching and health care institution at Hawassa University, where it is constructed near Lake Hawassa at 120 meters (Lencha et al., 2021) (Figure 1 and Figure 2).

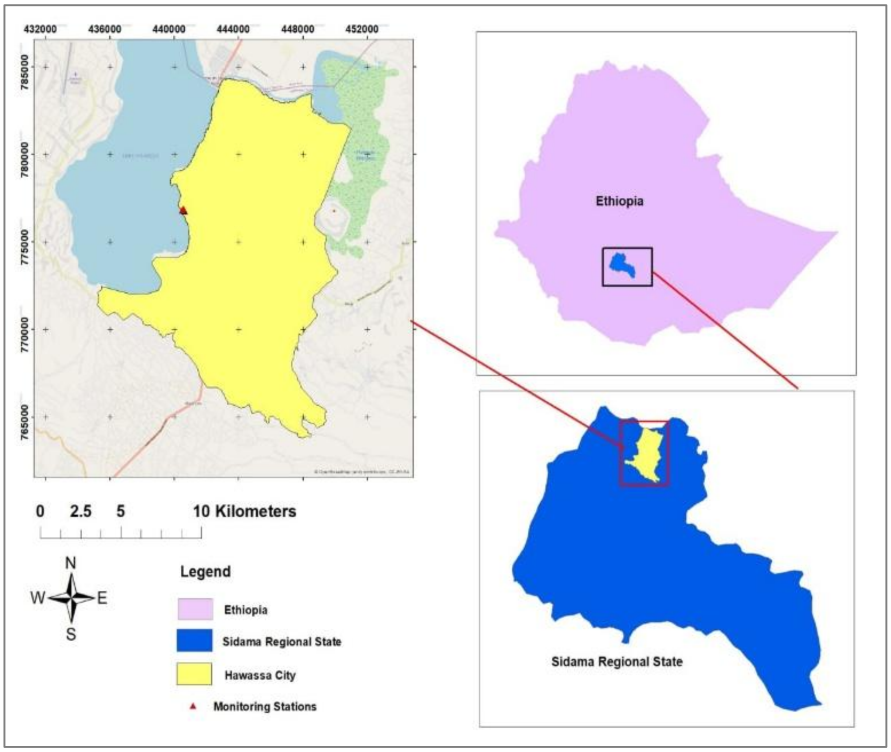

Figure 1. Geographical location of the study area

Figure 2. WSP of HRH

The hospital provides comprehensive healthcare service for many people in the region and neighboring communities. The HRH utilizes about 168.57 cubic meters (m^3) of water per day for its health care services, which can be translated to 553 litters (L) per bed^{-1} day^{-1} when considering the currently functioning 305 beds of the hospital. Out of the estimated water consumption volume, around 143.3 m^3 day^{-1} of wastewater is generated and flowing into the hospital's Wastewater Stabilization Pond (WSP) without any sort. The WSP comprises two facultative ponds connected in parallel, two maturation ponds in series, and one fishpond for fishery purposes. Conversely, following a hydraulic detention time of 66 days, the resultant effluent of around 139.61m^3 day^{-1} is discharged from the WSP to Lake Hawassa. Thus, the effluents which enter directly or indirectly to the lake have their own adverse effects on the lake environment (Bjorkli, 2004; Lencha & Tränckner, 2021).

The waste treatment plant with five trapezoidal ponds is shown in Figure 2 and Figure 3 two facultative ponds connected in parallel and three more in a series (two maturation ponds and a fish pond). The Facultative Ponds have the same dimensions, surface area and volume, and the Maturation Ponds are comparable in size. All four ponds are nearly the same in depth. The fish pond is the widest and deepest, and the largest (Fig. 3). The ponds are lined with PVC geomembranes to minimize infiltration. The waste stabilization system, through its two ponds, receives the effluent. The effluent then goes from the two ponds to the fish pond. Effluent from all the Ponds flows by gravity and eventually seeps into the ground.

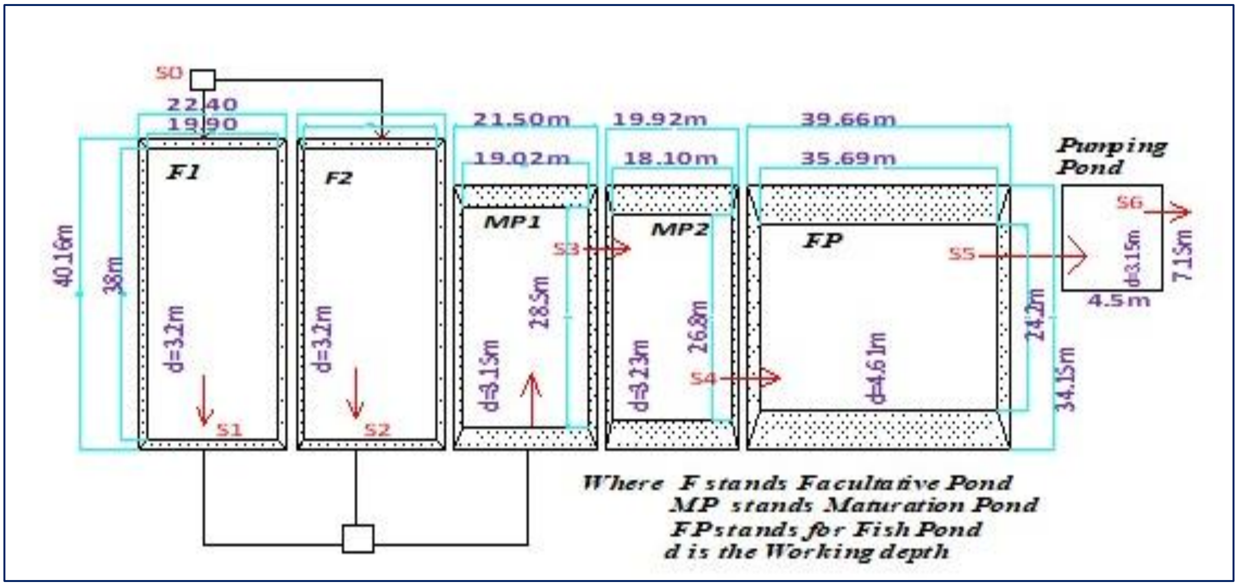

Figure 3. Schematic and dimensions of the WSP at Hawassa Referral Hospital

It is worth noting in the Marginal/Littoral Zones of the lake along the hospital effluent discharge route that there was certain color change from green to light yellow, which appeared to be due to chlorosis of the leaves of the aquatic floating.

2.2. Study Design and Period

The study was conducted on WSP at Hawassa Referral Hospital of Hawassa University, Ethiopia to trace a quality characteristic of the wastewater along the discharge route during March to October 2024.

2.3. Sample Collection and Analysis

2.3.1. Monitoring Sites

Wastewater samples for physicochemical and bacteriological analysis were collected from the influent and effluent of the WSP units using composite sampling. This is a straightforward method and better suited to demonstrate the average properties of wastewater influent and effluent over the study period. Eleven (11) sampling spots (S_0–S_{10}) were identified to assess the performance of each treatment unit as well as to observe any potential release of contaminants with the hospital effluent downstream to the lake environment.

Table 1. Description of wastewater sampling spots in Hawassa Referral Hospital's WSP units

MS	Description of Wastewater Sampling Spot	Latitude (Y)	Longitude (x)	Altitude (Z)
S_0	represents the point where influent enters the first two parallel Facultative Ponds (Distribution box)	776,730	440,658	1697
S_1	represent the sampling point directly from the outlet point of facultative pond one	776,763	440,637	1690
S_2	represent the sampling point directly from the outlet point of facultative pond two	776,780	440,622	1691
S_3	represent the sampling point directly from the outlet point of maturation pond one	776,811	440,608	1694
S_4	represent the sampling point directly from the outlet point maturation pond two	776,824	440,598	1694
S_5	represent the sampling point directly from the outlet point of each fishpond	776,855	440,573	1691
S_6	represent the sampling point at the outlet of the supplementary structure/pumping pond.	776,881	440,573	1690
S_7	represent the sampling point at 25m from S_6 where the effluent is transported via closed pipe and drains to the Lake.	776,847	440,524	1688
S_8	represent the sampling point where the effluent immediately joins the lake and the area becomes muddy, odorous, black in color, where grasses and other green living things seem gray in color.	776,826	440,509	1686
S_9	represent the sampling point along the effluent dispersal route to the lake	776,800	440,489	1685
S_{10}	represent the sampling point along the effluent dispersal route to the lake	776,792	440,486	1684

MS stands for monitoring sites

The sampling points were located by using GPS and google earth. At every sampling spot, triplicate samples were collected for this study as per the guidelines stipulated in standard procedures for water and wastewater sampling (APHA, AWWA, 2017). The description of the monitoring stations along the WSP units to the lake environment is as shown in Fig. 1 and Fig. 2 and Table 1.

2.3.2. Analysis of Physicochemical Parameters

The physicochemical characteristics of a total of 33 wastewater samples along the discharge route were measured. Physicochemical Parameters like Turbidity, Conductivity, Temperature and pH were determined onsite after their respective sampling. Turbidity and Conductivity of the wastewater and the lake samples were measured using Turbidity meter and conductivity meter (CO150). The temperature of the samples was ascertained with a handheld thermometer. A portable pH meter (Model HI 9024 HANNA) was used to determine hydrogen ion concentration (pH).

Chemical Oxygen Demand (COD) was measured using Closed Reflux by Colorimetric method and the 5-day Biochemical Oxygen Demand (BOD_5) was determined using a manometric respirometric method with a BOD sensor, in accordance with Standard Method 5210 D (Respirometric Method). Total Kjeldahl Nitrogen (TKN) by Kjeldahl Method, Phosphate (PO_4^{-3}), Sulfate (SO_4^{-2}), Nitrate (NO_3^-), Total Dissolved Solid (TDS), and SS (suspended solid) were measured with the help of Spectrophotometer (HACH DR3900). Dissolved Oxygen (DO) of the wastewater and the lake was measured using modified Winkler method.

Total levels of heavy metals (Chromium, Copper, Zinc, Lead, Nickel, Iron, Cadmium, mercury, and manganese) were measured with atomic absorption Spectrophotometer (Hach, model NOVAA400) according to standard methods. The digestion procedure for determining total heavy metals (Cr, Cu, Zn, Pb, Ni, Fe, Cd, Hg, and Mn) in wastewater samples prior to atomic absorption spectrophotometry (AAS) analysis typically involves acid digestion to liberate metals from particulate, organic, or complexed forms into a soluble state. Following standard methods (APHA/AWWA/WEF, likely Section 3030 E), a measured volume of well-mixed sample is acidified with concentrated nitric acid (HNO_3) and heated on a hot plate to near dryness to digest organic matter and dissolve metals.

The digestate is then cooled, filtered if necessary, adjusted to volume with deionized water, and clarified to produce a clear solution suitable for AAS analysis using the Hach NOVAA400 spectrophotometer. For mercury, a modified procedure involving oxidation with potassium permanganate/potassium persulfate was employed to ensure complete recovery without volatilization losses.

Bacteriological parameters have also been analyzed immediately in Hawassa University microbiology laboratory unit by multiple tube fermentation technique, where the concentrations of Total Coliform (TC) and Fecal Coliform (FC) bacteria were reported using the most probable number per 100ml (MPN/100ml). Water sample collection, handling, preservation and treatment techniques followed standard methods outlined in the American Public Health Association guidelines for the examination of water and wastewater (APHA, AWWA, 2017).

2.4. Statistical Analysis

The data for all parameters was analyzed by using XLSTAT 2016 and Microsoft Excel 2016. The descriptive data was presented by figures and tables (with mean, standard deviation, and range). One-Way ANOVA was employed to see significance variation ($p < 0.05$) between sampling spots for each variable. For those variables that revealed significant F-value, further mean separation was performed to reveal those sampling spots with significance variation for the parameter of interest. Besides, correlation coefficients were established to portray a correlation among variables and measure statistical significance between pairs of water quality variables (Lencha et al., 2021).

The influent and effluent of the hospital wastewater were compared to determine the treatment efficiency of the waste stabilization ponds. To do so, the performance of each WSP unit of every string (Facultative, Maturation, and a Fish ponds) as well as the overall performance efficiency of the wastewater treatment plant was calculated by using the following formula (Desye et al., 2022).

$$\text{Removal Efficiency } (\%) = \left(\frac{C_i - C_e}{C_i}\right) \times 100 \qquad \text{Equ… 1}$$

Where Ci is the influent concentration and Ce is the effluent concentration of pollutants. The influent and effluent in this study indicate the respective incoming and outgoing wastewater into and from every pond as well as the WSP.

3. Result and Discussion

3.1. Physicochemical characteristics of the Wastewater

3.1.1. Biochemical Oxygen Demand (BOD5)

The average BOD5 concentration of the raw wastewater from the Referral Hospital at S0 was 363.80 ± 57.78 mg/L while the corresponding value observed from the effluent of Waste Stabilization Ponds (S5) was 188.60 ± 12.73mg/L. These BOD5 values for the influent and effluent are comparatively higher than the standard. The effluent BOD level is roughly 38 times higher than the USEPA standard, which is a significant deviation. Discharging such high BOD effluent into a lake could lead to severe ecological consequences, including oxygen depletion, fish kills, and disruption of the aquatic ecosystem (Penn, M.R.; Pauer, J.J.; Mihelcic, 2013).

A study conducted by Moga et al., (2017) at Wolita Soddo Teaching Referral Hospital showed that the raw wastewater had a BOD5 of 204.14mg/L and the dumped effluent had a BOD5 of 46.16 mg/L. Conversely, the effluent from the waste stabilisation ponds, S5, had a BOD level statistically comparable ($p > 0.05$) to that of S6 and S7. It also had lower BOD levels than S1-S4 and higher BOD levels than S8-S10. The results of the study depicted in Table 2.

The pragmatic result for the present study has shown that the organic waste load of the hospital raw wastewater is a comparatively higher. However, a study by Beyene and Redaie (2011), reported a BOD_5 of 632 mg/L, which is higher than the same found for the current hospital raw wastewater and that the effluent BOD_5 (37.3 mg/L) was much lower than this result. Again, Lencha et al. (2021) reported an effluent BOD_5 of 56.4 mg/L. Sarafraz et al., (2007) also reported that the mean value of BOD_5 of raw wastewater in seven hospitals was 242.25 mg/L. The BOD5 concentration of the Bangkok Hospital raw effluent was 300 mg/L in a study by Mesdaghinia et al. (2009).

Table 2. The average (n = 3) and range of physicochemical parameters of the raw wastewater derived from Hawassa HRH and the effluent from Waste Stabilization Ponds

Parameter	**Raw Wastewater (S_0)**	**Effluent (S_5)**
	Mean + SD	**Mean + SD**
Temp.	21.8 + 0.53	25.2 + 1.29
pH	6.19 + 0.16	7.79 + 0.23
BOD_5	363.8 + 57.8	188.6 + 12.7
COD	875 +80.0	485.5 + 19.0
DO	0.59 + 0.16	1.01 + 0.25
Turb.	186.4 + 2.52	153.2 + 2.65
EC	438.2 + 55.26	312.7 + 13.05
TDS	736.9 + 32.35	467.2 + 9.17
TSS	539.3 + 46.20	282.9 + 5.86
NO_3^-	27.1 + 1.01	19.7 + 2.97
SO_4^{2-}	48.6 + 1.72	37.3 + 3.16
PO_4^{3-}	28.3 + 0.35	18.6 + 0.57
TKN	49.9 + 2.31	26.8 + 5.66

All units are in mg/L saving Temperature, Turbidity, EC, and pH which are expressed in °C, NTU, µS/cm, and unitless, respectively

3.1.2. Correlation Matrix Evaluation

Correlation coefficients show how strongly related two variables are. Coefficients close to -1 or +1 indicate a strong linear relationship. The correlation between parameters is described as strong (+0.8 to 1.0), moderate (-0.8 to -1.0), and weak (-0.5 to -0.8) (Shroff, P.; Vashi, R.T.; Champa neri, V.A.; Patel, 2015). As shown in Table **5**, the level of BOD_5 had a strong negative correlation with temperature, pH, and DO, having r values of (r = **-0.910**; r = **-0.976** and r = **-0.836**, $p < 0.05$), respectively. Conversely, BOD_5 revealed a strong positive relationship with COD (r = **0.916**, $p < 0.05$). This shows that BOD_5, which was associated with COD, is inversely correlated with temperature (Table 3) as well as pH and DO. As indicated in their respective discussion, temperature, pH, and DO are important for the reduction of BOD and COD. Alternatively, BOD gives an idea of the quantity of biodegradable organic matter present in an aquatic system, which is subjected to aerobic decomposition by microbes (Scholes et al., 2016).

Table 3. Correlation matrix Pearson (r) and alpha (p) values for physicochemical water quality parameters

Variables	Temp.	pH	BOD_5	COD	DO	TSS	TDS	EC	Turb.	PO_4^{3-}	SO_4^{2-}	NO_3^-	TKN
Temp.	1												
pH	0.947	1											
BOD_5	-0.910	-0.976	1										
COD	-0.928	-0.952	0.916	1									
DO	0.767	0.809	-0.836	-0.864	1								
TSS	-0.845	-0.937	0.965	0.874	-0.849	1							
TDS	-0.894	-0.964	0.983	0.928	-0.872	0.990	1						
EC	-0.773	-0.786	0.818	0.856	-0.858	0.781	0.834	1					
Turb.	-0.843	-0.879	0.902	0.940	-0.946	0.891	0.933	0.905	1				
PO_4^{3-}	-0.944	-0.973	0.958	0.981	-0.832	0.891	0.943	0.840	0.922	1			
SO_4^{2-}	-0.913	-0.933	0.939	0.947	-0.854	0.859	0.918	0.832	0.941	0.973	1		
NO_3^-	-0.832	-0.889	0.911	0.927	-0.955	0.930	0.952	0.884	0.983	0.901	0.902	1	
TKN	-0.924	-0.968	0.950	0.972	-0.851	0.891	0.938	0.787	0.928	0.985	0.981	0.910	1

Temp. stands for Temperature and Turb. for Turbidity. Values in bold are different from 0 with a significance level (p =0.05)

3.1.3. Chemical Oxidation Demand (COD)

The referral hospital's raw wastewater at S0 had an average COD concentration of 875 ± 80 mg/L. On the other hand, the mean level of COD observed for the effluent from the Waste Stabilization Pond at S5 was still high (485.5 mg/L), and it was also greater than fourfold that of the acceptable limit set by USEPA (2002). Then again, it was significantly different from the corresponding values for sampling points before and after it. This might be ascribed to the presence of notorious chemical and pharmaceutical substances that flow along with the wastewater, proceeding mainly from indiscriminate use and unscrupulous disposal of an array of chemicals and pharmaceuticals, as well as the wastewater containing different metabolites of the prescribed medicines.

A similar study reported that a mean COD concentration of 591.6 mg/L, with the range in different seasons of the same hospital wastewater being 245–1008 mg/L (Amouei et al., 2010; Beyene & Redaie, 2011; Sarafraz et al., 2007). Likewise, Mahassen et al. (2008), found that COD had an average value of 566.1 mg/L, with the maximum value being 782 mg/L, which is still within the typical ranges of COD levels indicated above.

Recalcitrant pharmaceuticals, such as antibiotics (e.g., ciprofloxacin, sulfamethoxazole), analgesics (e.g., ibuprofen, paracetamol), and antiepileptics (e.g., carbamazepine), significantly contribute to elevated COD levels in hospital wastewater due to their persistent chemical structures—often featuring aromatic rings, halogen substituents, or complex functional groups—that resist biodegradation in conventional treatment systems like WSPs (Verlicchi et al., 2010; Mir-

Tutusaus et al., 2017). These compounds are excreted by patients (up to 70-90% unchanged for certain drugs like carbamazepine), disposed via laboratory and cleaning activities, and exhibit low removal rates (<20-30%) in biological processes, leading to residual COD exceeding 400 mg/L post-treatment and promoting the proliferation of antibiotic resistance genes in receiving waters (Escolà Casas & Bester, 2015; McArdell et al., 2003).

Advanced oxidation processes (AOPs), such as ozonation, Fenton reaction, or photocatalysis, achieve 60-90% removal by generating hydroxyl radicals that mineralize these recalcitrants into simpler compounds, underscoring the necessity for hybrid or pretreatment strategies to enhance COD reduction and mitigate ecological risks in hospital effluents (Gadipelly et al., 2014; Aziz et al., 2025).

The hospital wastewater may contain several substances that are resistant to biological treatment plants, and some compounds discharged may also hinder the normal activity of microorganisms in the oxidation ponds.

Thus, hospital raw wastewater may affect the biological treatment process of the wastewater treatment plant. Accordingly, as indicated by Kajitvichyanukul and Suntronvipart (2006) and Varma et al. (2021) pretreatment of hospital wastewater that can transform recalcitrant organic compounds into easily biodegradable products is pivotal to improve the efficiency of biological treatment processes in Waste Stabilization Ponds.

3.1.4. Biodegradability Index

The BOD5/COD ratio, also known as the Biodegradability Index (BI), was calculated to assess the biodegradability of pollutants in hospital wastewater (Karungamye et al., 2023). Comparison of BOD and COD data is instrumental in identifying the existence of toxic conditions in a wastewater or to indicate the occurrence of biologically resistant wastes (Ziarati et al., 2022). The biodegradability of the raw wastewater, which was estimated using the initial value of the BOD5/COD ratio, was found to be 0.41. The Biodegradability Index (BI) of 0.41 for the raw hospital wastewater underscores a critical limitation in the WSPs performance, as values below 0.5 typically signal the presence of recalcitrant organic compounds that resist microbial degradation (Al-Sulaiman & Khudair, 2018; Kajitvichyanukul & Suntronvipart, 2006).

In hospital effluents, such low BI often stems from pharmaceuticals, disinfectants, and chemical residues that inhibit bacterial activity, delaying or hindering biological oxidation processes essential for effective treatment in facultative and maturation ponds (Karungamye et al., 2023; Zhang et al., 2020). This results in incomplete removal of BOD and COD, contributing to the observed inefficiencies, such as only 48.1% BOD reduction overall, far below the expected 70-90% for well-functioning systems (Shilton et al., 2005). Consequently, the ponds fail to adequately treat the wastewater, leading to persistent high pollutant levels in the effluent and heightened environmental risks to Lake Hawassa.

In contrast, the DO value of the effluent from WSP/S5 (1.01 ± 0.25 mg/L), which is statistically similar ($p > 0.05$) to those from S6 and S7, is considerably lower than the corresponding values for S8-S10, which represent DO observations from the marginal and littoral zones of the LH (Table 3 and Table 4). The rising trend in dissolved oxygen (DO) levels throughout the WSP, along the discharge path to the lake, and in the Marginal-Littoral zones is likely attributable to a decrease in biochemical oxygen demand (BOD), cyanobacterial/algal photosynthesis, surface aeration, improved aeration due to flow dynamics (slope and velocity), and dilution. The findings of this study are similar to those of Kayombo et al., (2012) and Paerl et al. (2016).

In the presence of sunlight, algal cells absorb CO_2 from the water and release O_2 as a by-product of photosynthesis (Christenson & Sims, 2011). This oxygen, along with that introduced through surface reaeration, is utilized by aerobic and facultative bacteria to break down organic matter in the upper water layer. The photosynthetic activity of pond algae leads to a diurnal fluctuation in dissolved oxygen levels. Following sunrise, photosynthetic processes cause a gradual increase in dissolved oxygen concentrations, which typically peak during the mid-afternoon. Subsequently, they decline, reaching a minimum at night when photosynthesis stops and respiratory processes consume oxygen (Boyd, 2015; Lawson, 2011; M. Wang et al., 2018).

The location of the oxycline shifts in response to changes in algal activity, as does the pH. During periods of peak algal activity, carbonate and bicarbonate ions react to supply additional CO_2 for algae, resulting in an excess of hydroxyl ions. Another study by Machihara et al.(2023) explores engineering sunlight-driven photosynthesis in algae to increase biofuel and other metabolite yields. This process can cause the pH to rise above 9, a level that is lethal to faecal bacteria (D. D. Mara, 2004; D. D. Mara & Pearson, 1999). Additionally, these conditions promote the removal of NH_3 through volatilization (EPA, 2002; Kadlec & Wallace, 2008).

3.1.5. Total Coliform (TC)

The average Total Coliform (TC) from the raw wastewater of HRH (S_0) was $8.17 \times 10^7 \pm 0.52 \times 10^7$ cfu/100ml and ranged between 7.6×10^7 and 8.61×10^7 cfu/100ml while the corresponding value of total coliform bacteria from the effluent (S_5) was $5.73 \times 10^6 \pm 0.96 \times 10^6$ cfu/100 ml which stretched up to 3.5×10^6 cfu/100ml (Table 4). The mean concentration of TC (S_0) statistically ($p < 0.05$) differed from the same measurements observed from the rest (S_1–S_{10}). In a similar study, Mesdaghinia et al.,(2009) average total coliforms were obtained in the raw wastewater of Razi Hospital (2.2×10^7 MPN/100mL) and Bahrami (3.8×10^8 MPN/100mL), fitting the 10^7–10^9 range from Verlicchi et al. (2010) Bahrami's maximum suggests exceptional contamination (e.g., surgical waste, patient density), while Razi's is more typical.

Table 4. The Average (N = 3) Coliform Bacteria (Cfu/100ml) of Hospital Wastewater Entering to and Leaving from the Waste Stabilization Ponds

Colifor Bacteria	**Influent to the pond (S_0)**	**Effluent from fish pond (S_5)**
	Mean $\pm$ SD	Mean $\pm$ SD
Total Coliform	$8.17 \times 10^7 + 0.52 \times 10^7$	$5.73 \times 10^6 + 0.96 \times 10^6$
Fecal coliform	$1.95 \times 10^7 + 0.13 \times 10^7$	$2.56 \times 10^6 + 0.13 \times 10^7$

The average value of total coliform bacteria measured from sampling site S_5 was higher than the acceptable limit (2400 cfu/100ml) set by USEPA (EPA, 2002). Wang et al. (2019) report wetlands treating 10^7 MPN/100mL coliforms using pH and NH_3 volatilisation for removal. Total coliform bacteria (TC), a collection of relatively harmless microorganisms, live in large numbers in soils, plants, and in the intestines of warm-blooded (humans) and cold-blooded animals. Also, describes the ubiquitous nature of total coliforms (TC) as environmental and enteric bacteria, emphasizing their broad distribution and generally non-pathogenic status (Mesdaghinia et al., 2009). USEPA (United States Environmental Protection Agency (USEPA), 1986) found that TC levels > 2000 - 2400 MPN/100 mL in recreational waters were correlated with increased rates of gastrointestinal illness. Fecal coliforms (E. coli) were prioritized, but TC limits remained in older guidelines, indicating severe risk if reaching recreational waters. Jennings et al.(2018), note that any detectable total coliforms (TC) (>10 MPN/100mL) in surface waters signal potential fecal contamination, though health risks are minimal below 100–200 MPN/100mL unless pathogens are present. Gruber et al.(2017), argue that TC presence flags sanitary issues (e.g., regrowth or contamination), but direct health risks require faecal-specific markers (*E. coli*, enterococci). At <100 MPN/100mL, risk is negligible in recreational waters.

3.1.6. Faecal Coliform (FC)

The average Fecal Coliform (FC) from raw wastewater HRH (S_0) was $1.95 \times 10^7 \pm 0.13 \times 10^7$ cfu/100ml and reached up to 2.1×10^7 cfu/100ml. It was statistically ($p < 0.05$) different from the same measurements of FC investigated from other sampling spots (S_1–S_{10}). On the other hand, the corresponding level of FC for the final effluent (S_5) was $2.56 \times 10^6 \pm 0.13 \times 10^7$ cfu/100ml and ranged between 0.12×10^6 and 1.1×10^6 cfu/100ml (Table 5). The value of FC from Fish Pond (S_5) was about 67-fold greater than the standard (1000cfu/100ml) set by USEPA (EPA, 2003).

Table 5. Mean (n = 3) Coliform Bacteria Levels (cfu/100ml) of Wastewater across the Sampling Spots

MS	Total coliform (cfu/100ml)	Fecal coliform (cfu/100ml)
S_0	$8.17 \text{ x}10^{7a}$	$1.95\text{x}10^{7a}$
S_1	$9.10\text{x}10^{6b}$	$5.40\text{x}10^{6b}$
S_2	$9.03 \text{ x}10^{6b}$	$4.20\text{x}10^{6bc}$
S_3	$8.40\text{x}10^{6b}$	$3.06\text{x}10^{6cd}$
S_4	$8.33\text{x}10^{6b}$	$2.80\text{x}10^{6cd}$
S_5	$5.73\text{x}10^{6bc}$	$2.56\text{x}10^{6ce}$
S_6	$4.37\text{x}10^{6bcd}$	$2.17\text{x}10^{6def}$
S_7	$2.80\text{x}10^{6cd}$	$0.67\text{x}10^{6eg}$
S_8	$1.67\text{x}10^{6cd}$	$0.29\text{x}10^{6fg}$
S_9	$0.99\text{x}10^{6cd}$	$0.28\text{x}10^{6fg}$
S_{10}	$0.61\text{x}10^{6d}$	$0.113\text{x}10^{6g}$

Fecal Coliforms often do not cause illness directly, but make good indicators of harmful pathogens in water bodies (EPA, 2002). When fecal contamination exists in a water body used for primary contact, the main route of exposure to illness-causing organisms is through direct contact with contaminated water while swimming, most commonly through accidental ingestion of contaminated water (Hagedorn et al., 1999). Dufour et al. (2017) emphasized that accidental ingestion of 10-20 ml per swim continues to be the dominant route of exposure, echoing the findings of Hagedorn et al. (Hagedorn et al., 1999). However, they add modern microbial source tracking (MST) to identify sources of contamination - such as sewage vs. agricultural runoff. This process is used to describe the process by which faecally contaminated water is taken into the body via the mouth. Swimmers in faecally contaminated waters are at high risk for waterborne diseases frequently caused by ingestion (Geldreich, 1970). Iwamoto et al. (2005) examined the microbial risks in faecally contaminated lakes. They find that swimmers are at increased risk of Shigella and Salmonella following faecal pollution events.

3.2. Removal Efficiency of the Waste Stabilization Ponds

3.2.1. Performance of Facultative Ponds

Facultative ponds had enhanced performance in terms of downsizing FC, TC, BOD, TSS, and TDS than that of either Maturation Ponds or Fish Pond. The removal efficiencies reported for individual pond types in Table 6 and throughout Section 3.5 represent the percentage reduction achieved within that specific unit (or parallel units for Facultative Ponds), calculated as the difference between the influent and effluent concentrations for that pond type. 'Fnet' refers to the net (cumulative) removal after the Facultative Ponds (first treatment stage), and 'MPnet' after the Maturation Ponds. The Facultative Ponds, as the initial treatment units receiving raw hospital wastewater, achieved the highest individual reductions in parameters such as faecal coliforms (75.4%), BOD (27%), TSS (34%), and TDS (23.4%), contributing the largest fraction of overall organic and solids removal. In contrast, Maturation Ponds excelled in sulphate and total Kjeldahl nitrogen reduction, while the Fish Pond performed best for COD (33.9%) and phosphate (21.6%).

The BOD removal of WSPs (27%) was lower than the expected value by Shilton et al. (Shilton et al., 2005) and the report of other investigators (Abis & Mara, 2003). A removal rate of 27% is below the expectations of earlier studies by Shilton et al. (2005), who reported typical BOD removal rates for well-designed WSPs of 70–90%. Mersha et al. (2020) studied WSPs in semi-arid regions and found BOD removal of 65–80% in well-maintained systems. However, they note a decline to 20–30% in ponds with poor algal growth or short retention times. Taken together, these studies show that while WSPs can achieve the high BOD removal rates reported by Shilton et al.(2005) and the report of other investigators (Abis & Mara, 2003; I. Hodgson, 2008). Real-world performance often falls short due to factors such as hydraulic inefficiencies, overloading, or environmental constraints. The findings of 27% are in line with this lower end of the range and may reflect design or operational challenges.

Then again, Facultative Ponds have shown very poor performance in reducing COD (3.5%). It is due to the aerobic process that is responsible for the biological oxidation of the wastewater. (I. Hodgson, 2008). Similarly, the removal of TSS (34%) and TDS (23.4%) was observed from the Facultative Ponds (Table 6). Chen et al. (2023) Reported an average COD reduction of 5-10%, well below the 50–70% that would be expected from a well-functioning aerobic process, and attributed this to insufficient dissolved oxygen (DO) levels due to high organic loading and poor mixing. TSS removal was moderate at 30–40% and TDS barely moved (20–25%), suggesting limited sedimentation and dissolution capacity - consistent with these study findings. Lawlor and Tezara (2009) linked the poor aerobic performance to low algal photosynthesis under cloudy conditions, which reduces the oxygen available for BOD/COD degradation (in contrast to the ideal of Hodgson). TSS removal averages 32% and TDS removal averages 24%, with sediment build-up and lack of mechanical aeration reducing efficiency.

Table 6. Unit performance of the Waste Stabilization Ponds (%) for the important wastewater parameters

Parameters	Waste Stabilization Ponds						
	Facultative Pond			Maturation Pond (MP)			Fish Pond (FP)
	F_1 (%)	F2 (%)	FP_{net}(%)	MP_1 (%)	MP2 (%)	MP_{net}(%)	FP (%)
BOD_5	25.4	30.2	27	14.7	3.2	17	13.6
COD	2.2	4.7	3.5	3.2	10	12.9	33.9
TSS	32.2	35.9	34	7	4.9	11.7	10
TDS	21.9	24.3	23.4	3.4	4.9	8.3	9.9
Turbidity	2.2	6.4	4.8	2.2	2.9	5.1	7.9
PO_4^{3-}	7.3	9	8.1	7.2	1.3	8.5	21.6
SO_4^{-2}	2.26	5.3	3.8	8.02	11.2	18.2	2.3
NO_3^-	10	11.1	10.5	5.56	4.8	10.1	9.4
TKN	3.8	9.2	6.5	19.5	14.9	30.1	17.8
Fe^{+2}	29.8	31.3	30.5	7.5	13.9	20.4	10.8
Cr^{+6}	14.3	28.5	21.4	-8.3	16.7	9	20
Cu^{+2}	14.3	28.5	21.4	-8.3	16.6	9	20
Mn^{+6}	4.1	8.3	6.3	-6.3	12.5	6.6	3.3
Zn^{+2}	5.9	11.7	8.8	3.2	5.3	8.3	1.4
TC	88.8	88.9	88.9	7.3	0.8	8.05	30.9
FC	72.3	78.5	75.4	36.3	8.4	41.7	8.6

Where, Fnet is the combined efficiency of Facultative ponds, and MP_{net} is the combined efficiency of Maturation ponds.

On the other hand, nutrient removal of Facultative Ponds in HRH was (8.1%, PO_4^{-3}), (3.8%, SO_4^{-2}) and (10.5%, NO_3). Hodgson (2000) reported that removal efficiencies of 48.8% and 94% for NO^{3-} and $PO_4^{-3,}$ respectively, were observed in Ghana. Rigotto et al.(2023) investigated nutrient removal in facultative ponds for the treatment of domestic wastewater in Brazil. They reported low efficiencies of 10 % for PO_4^{3-}, 5 % for SO_4^{2-} and 12 % for NO_3^- and attributed these to limited algal uptake and poor anaerobic-aerobic cycling. Compared to Hodgson's (2000) results for Ghana, they suggest that high organic loading and short residence times reduce nutrient assimilation, a possible explanation for the findings of HRH. Monroy-Licht et al. (2024) studied nutrient dynamics in facultative ponds enhanced with floating macrophytes. Without enhancements, they find dismal removal rates of 9% for PO_4^{3-}, 4% for $SO_4^{2-,}$ and 11% for $NO_3^{-,}$ which mirror the findings of this study. With green upgrades, efficiencies rise to 50–60% for NO_3^- and 80–90% for PO_4^{3-}, Hodgson's Ghana benchmarks, highlighting design as a critical factor.

In view of this, the Facultative Ponds in the present study had poor performance on nutrient removal. Likewise, HRH Facultative Ponds had a lower performance of removing TKN (6.5%) than that of Moazzam and Altaf (2007). In the same way, Facultative Ponds removed 75.4% of FC from the raw wastewater of the hospital. In the study by Moazzam and Altaf (2007), the maximum efficiency of Facultative Ponds in removing faecal coliforms reached up to 99%. Alam (2018), studied facultative ponds in Bangladesh and found TKN removal of 7–10%, which was attributed to high organic loading and anaerobic dominance, while FC removal reached 75–80%.

In general, Facultative Ponds under the present study had poor performance regarding all the parameters (organic matters, nutrients, and pathogens) except that of TC. The low removal efficiency of Facultative Ponds in terms of organic matter, nutrients, and pathogens was mostly attributed to short-circuiting, high sludge accumulation, and the scum that covers the top surface of the Pond.

3.2.2. Performance of Maturation Ponds

Maturation Ponds revealed improved performance in trimming down SO_4^{-2} and TKN than that of the corresponding removal capacity of Facultative and Fish Ponds. On the other hand, Maturation Ponds also removed 12.9% of COD and 17% of BOD level (Table 6). Lima et al. (2024) Evaluated maturation ponds in Brazil and reported better SO_4^2 removal (15–20%) and TKN reduction (10–15%) than facultative ponds (5–8% for both) due to extended retention and microbial activity. However, COD removal was 10-14% and BOD 15–18%, consistent with the findings of this study. They agree with Mara. (D. Mara, 2017) who found low algal biomass due to nutrient depletion and Daphnia predation, with effluent BOD largely derived from algae (60–75%).

As Table 6 indicates, Maturation Ponds in the present study removed 10.1% (NO_3^-), 8.5% (PO_4^{-3}), and 11.7% (TSS). These low efficiencies, similar to the findings of this study, are associated with sparse algal growth due to nutrient competition and shading, which reduces pH for ammonia volatilisation (Blier et al., 1995; Gomez et al., 1995; S. A. Silva et al., 1995). In contrast, the higher rates reported by Olukanni and Ducoste (2011) Probably reflects robust algal activity, suggesting that the pond design in HRH or influent limits algae.

Likewise, both Maturation and Facultative Ponds in the present study had low performance regarding heavy metals. In particular, Maturation Ponds revealed poor performance on removing Cu^{2+} (9%) and Cr^{6+} (9%) compared to that of Facultative and Fish Ponds (Table 6 and Fig. 4) and well below Oliver & Cosgrove's (Oliver & Cosgrove, 1975) 60% Cu^{+6}. They attributed this to low algal and microbial activity due to nutrient depletion and sludge accumulation, with negative Cr removal (-3%) in one pond linked to sampling inconsistencies or hydraulic overload, paralleling our findings. Negative removal efficiencies for heavy metals, such as the -6.3% observed for manganese (Mn) in the maturation ponds of HRH's waste stabilization ponds, indicate a net increase in metal concentrations from influent to effluent, signifying that the pond acts as a source rather than a sink for the contaminant.

This phenomenon is commonly caused by sediment or sludge re-suspension due to wind mixing, hydraulic disturbances, or biological activity; desorption and repartitioning of metals from organic matter or sludge triggered by pH fluctuations (e.g., algal-induced alkalinity); internal loading from redox shifts creating anaerobic conditions at the sediment-water interface, solubilizing metals like Mn from oxides; and operational issues such as short-circuiting, overloading, poor pond geometry (low length-to-width ratios), excessive depth promoting anoxia, and lack of regular desludging. Supporting literature, including Edokpayi et al. (2021) reporting extreme negative Mn removals (-1060%) linked to long-term sludge accumulation, Mahapatra et al. (2022) attributing negatives to sludge desorption, Mwanyika (2016) and Ho et al. (2017) highlighting redox-driven releases, and Desye et al. (2022) connecting inefficiencies to design flaws in Ethiopian WSPs, consistently demonstrates that these mechanisms are prevalent in overloaded or poorly maintained maturation ponds, exacerbating downstream risks like metal bioaccumulation in receiving waters such as Lake Hawassa.

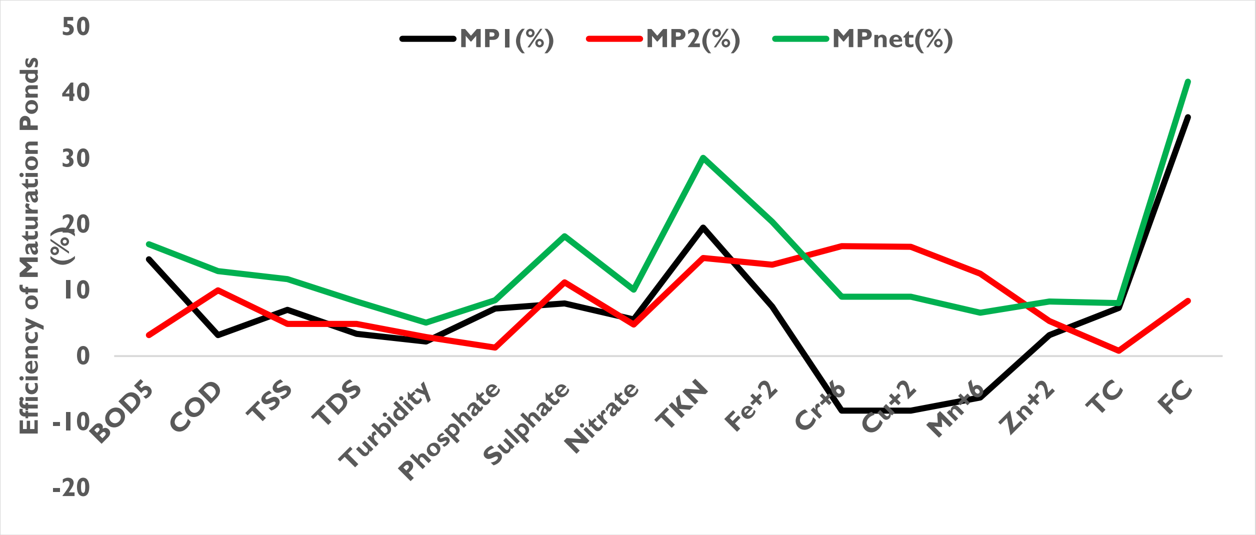

Figure 4. Removal efficiency of Maturation ponds pertaining to different parameters

As Table 6 and Figure 4 represent, Maturation Ponds had poor performance of downsizing TC (8.05%) and FC (41.7%). Kayombo et al., (2005) Reported TC removal of 10 to 15% and FC removal of 40 to 45%, which is consistent with the findings of this study. The poor performance is attributed to high organic loading and low sunlight penetration due to scum. In contrast, Moazzam and Altaf (2007) reported 87% TC and 74% FC, probably due to the optimized geometry and climate of Karachi. Shilton et al.(2005) reported TC removal of 7–12% and FC 35–42%, close to the results (8.05% and 41.7%) of this study. They link the low efficiency to short retention times and poor wind mixing, which limits algal activity and UV exposure. Moazzam and Altaf's higher rates suggest better inflow/outflow design, which is absent in these ponds.

3.2.3. Performance of Fish Pond

As Table 6 and Fig. 5, reveals Fish Pond exhibited improved performance about reducing COD (33.9%) and PO_4^{3-} (21.6%) when compared to the Facultative (3.5% COD, 8.1% PO_4^{3-}) and Maturation (12.9% COD, 8.5% PO_4^{3-}) Ponds. Concerning TC, Cr, and Cu, both Facultative and Fish Ponds had a more palpable removal capability than that of Maturation Ponds.

Carbonell (2024) reported COD removal of 30-35% and PO_4^{3-} reduction of 20-25%, outperforming facultative ponds (5–10% COD, 7–12% PO_4^{3-}) and maturation ponds (10–15% COD, 8-13% PO_4^{3-}). Fish activity enhanced organic degradation and nutrient uptake, while TC removal reached 70-80%, exceeding that of the maturation ponds (10–20%).

Conversely, the Fish Pond removed perceptibly low fraction of FC (8.6%), Fe (10.8%), Mn (3.3%) and Zn (1.4%) than that of Facultative and Maturation Ponds (Table 6 and Figure 5).

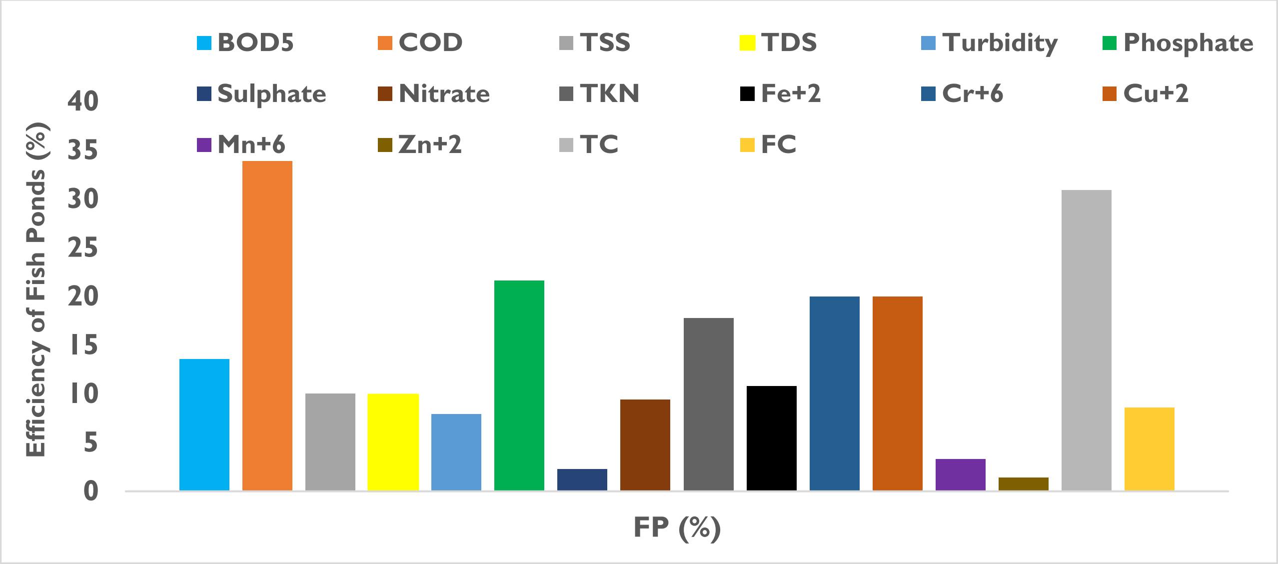

Figure 5. The removal efficiency of Fish Pond pertaining to different parameters

Regarding some parameters such as NO_3^- and turbidity, all the ponds (Facultative, Maturation and Fish Ponds) presented comparable and low removal efficiency over the other parameters (Table 4.8). Similarly, both Facultative Pond 1 and Fish Pond had poor performance of removing SO_4^{-2} (3.8%, 2.3% respectively). Liu et al. (2023) reported FC removal of 5-10%, Fe 8-12%, Mn 3–5% and Zn 1–3%, fish ponds in Chinese aquaculture systems, which is consistent with the results of this study (8.6%, 10.8%, 3.3%, 1.4%). They found that the fish activity led to resuspension of sediment, increased turbidity, and metals in the pond compared to the facultative pond (FC 40–50%, Fe 20–30%). NO_3^- and turbidity removal was low in all ponds (10–15%), suggesting limited microbial or sedimentation capacity - consistent with the results of this study.

3.2.4. The Overall Performance of Waste Stabilization Ponds

During the study intervals, the WSP average removal efficiency of TC and FC was 92.9% and 86.8% with average effluent bacterial count of 5.73 x 10^6 cfu/100ml and 2.56 x 10^6 cfu/100ml, respectively. Which didn’t attain the effluent Standard set by USEPA (2002) for Lake water as (2400cfu/100ml and 1000cfu/100ml) in that order. The FC removal in WSP is a combination of different effects, which depend on the type of WSP, i.e. anaerobic, facultative or maturation, and additional factors such as wastewater temperature, pond depth, percentage of water surface covered by algae and wind direction, all of which prevail and interact to a different degree under different circumstances. Of these, the WSP in this study had a better performance in removing bacteriological parameters than other parameters investigated in this study.

On the other hand, the BOD and COD removal efficiency of the waste stabilization pond was 48.1% and 44.5% respectively (Fig. 6), with BOD and COD levels of 188.60 ± 12.7 and 485.50 ± 19.00mg/L.

According to Kayombo et al. (2005), the overall achievement of WSP on BOD removals was > 90% and the COD removal rate was about 94%. Al Kholif (2023) Reported BOD removal of 85-92% and COD removal of 80-87% in WWTPs treating domestic wastewater. The high efficiencies were associated with long retention times (>20 days), warm climates and simple wastewater, in contrast to the lower performance of WSPs in HRH, probably due to complex and resistant organic substances from hospital sources. Moga et al., (2017) Found BOD removal of 40-60% and COD removal of 45-65% in WSPs treating hospital wastewater.

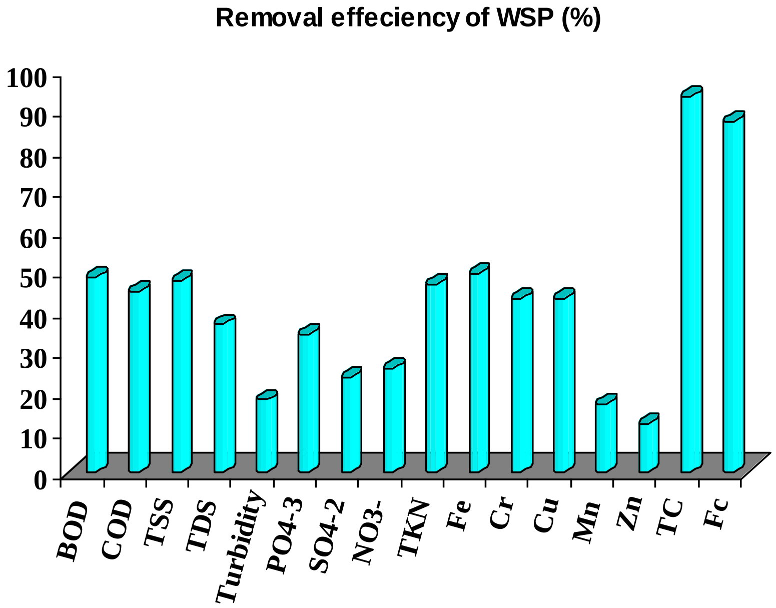

Figure 6. The overall performance of WSP for different Parameters

Resistant organic substances were identified as the main barrier to biological degradation. Comparatively, WSP in the current study showed low performance in removing BOD and COD. The lower removal efficiency of the waste stabilisation ponds for BOD_5 may be due to the type of wastewater (which contains the wastewater from the main hospital/laboratory, student dormitory, guest house, cafeteria, and laundry). The hospital contains several organic substances that are resistant to biological degradation. These resistant compounds may affect the biological treatment process of the wastewater treatment plant.

Likewise, the WSPs in the present study had low performance in removing TSS (47.5%) and TDS (36.5%). A similar result was obtained by Sinn and Lackner (2020), the average removal efficiency of the TSS Waste stabilization pond was 44.3%. Also, the mean efficiencies of the Waste stabilization Ponds of TSS were found to be 76.7% to 80.1% (Goyal & Mohan, 2013) Elsewhere. The lower removal efficiency the Ponds was mainly due to the high suspended solids sourced from the hospital wastewater; hence, the wastewater entered the WSP without primary/preliminary treatment.

As presented in Figure 6, the WSPs had low performance regarding PO_4^{3-}, NO_3^-, TKN, and SO_4^{-2} with average removal efficiency of 47.5%, 36.5%, 34.1% and 19.1%, respectively. It can be seen that the HRH waste stabilisation ponds had poor performance on nutrient removal. This may have been caused by the sludge that covered the surface of the pond, limiting the biological activity within the pond. Desye et al. (2022) reported TKN removal of 79% (effluent 17.4 mg/L), PO_4^{3-} removal of 69.2% (effluent 4.8 mg/L), and NO_3^- removal of 30% in a WSP system. Lower NO_3 removal was associated with limited denitrification due to surface scum and high organic loads, which is consistent with the low nutrient removal observed in this study. Besides, they also reported TKN removal of 79% (effluent 17.4 mg/L), PO_4^{3-} removal of 69.2% (effluent 4.8 mg/L), and NO_3^- removal of 30% in a WSP system. Lower NO_3^- removal was associated with limited denitrification due to surface scum and high organic loads, which is consistent with the low nutrient removal observed in this study. Shaheen et al.(2024) reported nutrient removal efficiencies of PO_4^{3-} 16.18%, NO_3^- 36.92% and TKN 42.04% across treatment stages in an Egyptian WSP. The study found that anaerobic conditions and scum layers reduced nutrient removal, particularly for PO_4^{3-} and NO_3^-, reflecting the poor performance observed in this study.

Regarding heavy metals, the present study WSPs had a slightly enhanced performance on removing Fe (avg., 49.02%), Cr (42.8%), and Cu (avg., 42.8%) when compared to other heavy metals such as Mn and Zn. Likewise, the WSP had zero efficiency in removing some heavy metals (Pb, Hg, Ni, and Cd) since they were uniform throughout the treatment system. Mwanyika (2016), evaluated Tanzanian WSPs treating domestic wastewater. Heavy metal removal was variable: Fe removal averaged 54%, Cu 48% and Zn 35%. Pb, Cd, and Ni showed efficiencies below 20%. The study attributed the low removal rates to limited adsorption and sedimentation under high organic loads, which is consistent with the poor performance of WSPs of HRH for most metals except Fe, Cr, and Cu. Kaloudas et al. (2021), reported that the total heavy metal removal efficiencies of 88%, 79%, 90% and 70% for Zn, Pb, Cu, and Cd, respectively, were achieved by WSPs. Generally, the WSPs in the present study had poor performance in removing heavy metals.

In general, the WSPs in this study showed significantly poor performance in treating the hospital's raw wastewater. This could be due to the high surface loading or low desludging rate, short circuiting, and the presence of suspended solids of different sizes in the system. In this case, there is no provision for pre-treatment (screening and grit removal), which adversely affects the ponds due to excessive scum and a higher rate of sludge accumulation. Another cause of underperformance may be the design of WSPs. In its investigation, the working depth of the first two pods (Facultative Ponds) was 3.2m, the next two Ponds (Maturation Ponds) had working depths of 3.15m and 3.23m, and the last pond (which is considered as Fish Pond) had a working depth of 4.61m (Figure 3).

According to Mara (2017), the depth of an anaerobic pond is usually 2m to 5m, whereas for a Facultative Pond, it is 1m to 2m, and about 1m to 1.5m depth is also recommended for Maturation Ponds. Additionally, the WSPs and constructed wetlands design manual also recommended that the depth of Anaerobic, Facultative, and Maturation Ponds be 2m to 5m, 1m to 2m, and 1m to 1.5m, respectively. Besides, depths greater than 2.5 m in facultative ponds often resulted in anaerobic conditions, reducing COD removal to 45-60% and nutrient removal to <50%, reinforcing the hypothesis of design failure in HRH. Rather, all the Ponds are approaching the Anoxic/Anaerobic Pond, and hence it might lead to the Ponds' failure.

According to Mara (2017), Facultative Ponds and Maturation Ponds should be geometrically designed to have a high length-to-width ratio (up to 10:1) to simulate a hydraulic plug flow regime. But, the geometric designs (length-to-width ratio) of the Facultative and Maturation Ponds in the current study were about a 2:1 and approximately a 1:1 ratio for the Fish Pond. It is obvious that the inappropriate geometric designs (length-to-width ratio) of the Ponds (Facultative, Maturation and Fish Ponds) were one of the factors that affect the treatment capacity of the current hospital WSP. Al Kholif et al. (2023), achieved BOD removal of 85-92%, higher than ponds with ratios closer to 1:1 (60-70% removal). The higher L:W ratio minimized short-circuiting, supporting the plug flow recommendation of Mara (1997) and suggesting that a 2:1 and 1:1 ratio may indeed limit the efficiency of this study. Besides, Desye et al. (2022) reported that a facultative pond with an L: W ratio of 2:1 achieved BOD removal of 75%, while a maturation pond at 1.5:1 had nutrient removal below 50%. Higher ratios (up to 8:1) in a parallel system improved efficiency by 15-20%, in line with Mara's guidelines and suggesting that the 2:1 and 1:1 ratios of this study are likely to impede plug flow and treatment capacity.

Furthermore, a critical design deficiency in the HRH WSPs lies in the lack of adequate anaerobic pre-treatment stages, which are essential for initial organic matter breakdown and solids settlement in high-strength effluents like hospital wastewater, thereby preventing overload and stratification in downstream facultative and maturation units (Ho et al., 2017; Edokpayi et al., 2021).

This flaw is compounded by potentially flawed inlet and outlet structures that fail to ensure uniform wastewater distribution, leading to preferential flow paths and reduced effective volume utilization across the pond surface (Mahapatra et al., 2022). Moreover, the absence of baffles or dividers to promote better mixing and minimize dead zones further impairs biological processes, as it limits oxygen transfer and microbial contact, resulting in suboptimal degradation of recalcitrant compounds and persistent effluent quality issues (Desye et al., 2022).

3.3. Potential Contamination of the Hospital Effluent on the Marginal and Littoral Zones of Lake Hawassa along the Discharge Route

Hawassa Referral Hospital wastewater, after its treatment by the WSPs (and eventually turned out to be the effluent), is directly discharged to the nearby receiving environment (the Marginal-Littoral Zones of Lake Hawassa). Like things, any potential environmental impact ascribed to the likely contaminants on the environment pivots on how sensitive the receiving environment is, as well as the amount and nature of contaminants present in the effluent that is being dumped into it. Regarding the latter, the type of treatment plant employed and the efficacy of the same to deal with the wastewater constituents are essential.

Even if the mean BOD_5 values observed from the Marginal and Littoral Zones (71.6–102.1 mg/L) were significantly ($p < 0.05$) lower than that of the effluent from the WSP (S_5), due in part to the dilution as well as enhanced process of BOD removal, they remained sizable. In general, the considerable levels of BOD_5 observed in such a sensitive environment may have an undesirable effect on the part of the Hawassa Lake along the discharge route. Moreover, the high level of BOD from the effluent may deplete oxygen in the dispersal route of the lake. Hodgson (2008)It is suggested that the effluents with high concentrations of BOD can cause depletion of natural oxygen resources, which may lead to the development of septic conditions in the receiving water body. Nkwocha et al.(2013), reported that the BOD5 effluent from the WSP hospital ranged from 80-120 mg/L, causing DO levels in a downstream lake to fall below 3 mg/L along the discharge path (Franklin, 2014). The study highlighted the risk of anaerobic zones under such conditions, corroborating the findings of this study.

The DO levels measured for the Marginal-Littoral Zones ranged from 1.28 to 2.36 mg/L. According to Chin (2006), saturation of DO in water for temperatures of 20 and 25°C (which are approximately the temperatures of these zones) is 9.1 and 8.2 mg/L. DO is vital for aquatic ecosystems, and it is needed by aerobic organisms for metabolism and chemical reactions (Carr & Neary, 2008). But, releases of oxidisable organic matter to water bodies deplete DO, causing fish kills, odours, and impacts on water quality. Most fish do well in water at or above 5 mg/L DO; below 5 mg/L, some game fish become stressed (Franklin, 2014). Besides, Al Kholif et al. (2023), reported effluent DO of 2-3 mg/L despite dilution, well below the fish tolerance level of 5 mg/L. High organic inputs consume DO, risking anaerobic conditions and odours, with downstream DO depletion affecting aquatic metabolism, underscoring concerns about ecosystem health (Carr & Neary, 2008).

Apparently, the high mean COD levels in the Marginal (444.4 mg/L) and Littoral (295.4 and 236.0 mg/L) Zones may be attributable to the recalcitrant organics that, for good measure, defied the WSP treatment system, and may still contain potentially toxic chemicals/pharmaceuticals and other hazardous wastes, which could essentially present risk to organisms inhabiting such habitats.

Moreover, Hospital wastewater includes a great variety of micro-contaminants that are chemicals, disinfectants, and specific detergents resulting from diagnosis, laboratory, research activities, and medicine excretion by patients (Carraro et al., 2016). Kumar et al. (2020) found pharmaceutical residues at levels of 50-100 µg/L in hospital effluents, along with disinfectants and antibiotic-resistant bacteria. They linked these contaminants to endocrine disruption and ecosystem damage and advocated the use of hybrid systems (e.g., membrane bioreactors) to improve removal efficiency.

Due to high turbidity of the effluent (153.2 NTU) from the WSP, there was a palpably high level of turbidity observed from the Marginal (121.5NTU) and Littoral (78.9 and 57.6NTU) Zones of Lake Hawassa. Turbidity can also limit plant growth, typically in the Marginal/littoral Zones of the lake. Turbidity may indicate the presence of disease-causing organisms. These organisms include bacteria, viruses, and parasites, which can cause symptoms such as nausea, cramps, diarrhea, and associated headaches. (Kajitvichyanukul & Suntronvipart, 2006).

The moderately elevated level of NO_3^- from the WSP (19.73 mg l^{-1}) apparently contributed to the parallel modestly high levels observed in Marginal (18.3 mg/L) and Littoral (11.5 mg/L and 8.1 mg/L) Zones of the lake. An excess amount of NO_3^- results in eutrophication of lakes, which can cause excessive algal blooms, bacterial growth, and aquatic vegetation growth, depletion of dissolved oxygen, and an aesthetically unappealing water body in aquatic ecosystems. Lencha et al. (2021), highlighted the role of eutrophication in degrading lake ecosystems through macrophyte overgrowth, cyanobacterial proliferation, and cyanotoxin release. They report reduced recreational use due to physical obstruction and aesthetic problems (e.g., scum, odours). The literature highlights nutrient enrichment - often from agricultural or wastewater sources - as a key driver, consistent with our focus on impacts on water systems.

High average levels of PO_4^{3-} were investigated in the Marginal (14.15 mg/L) and Littoral (13.32 and 12.45 mg/L) Zones. Phosphorus in the form of phosphate is the limiting nutrient in eutrophication of lakes, which makes its removal from wastewater necessary before discharge. (2021). These phosphates include organic phosphate, polyphosphate (particulate P), and orthophosphate (inorganic P); orthophosphates are readily utilized by aquatic organisms. (Di Capua et al., 2022). Al Kholif (2023), found that WSP effluent contained orthophosphate levels of 2-5 mg/L, contributing to eutrophication in downstream lakes. It highlighted the bioavailability of orthophosphate to cyanobacteria and noted that inadequate removal led to algal blooms, eutrophication, reduced oxygen (DO <4 mg/L), or elevated BOD and biodiversity (Breen et al., 2018), consistent with the findings of this study.

The average levels of all heavy metals (except Cr, Cu, and Hg) released from the effluent of WSP were slightly higher than the maximum contaminant level set by USEPA (2002). The discharge of heavy metals in the lake has an obvious impact on the aquatic systems (Akoto et al. 2009). Long-time exposure to toxic trace metals such as cadmium, chromium, copper, lead, mercury, nickel, and zinc, even at low concentrations, can be deleterious to human health. The study highlighted acute toxicity to fish and chronic risks to human health through dietary exposure, supporting Swielticki et al. (1996) and Akoto et al. (2009) on long-term effects. Kumar et al. (2020), found Hg, Cd, and Zn in hospital effluents at levels causing acute toxicity to aquatic organisms and accumulating in lake sediments. It highlighted chronic human exposure risks (e.g., neurological damage from Hg), with implications for lake ecosystem health.

Due to the high levels of the Total and Fecal Coliforms emanating along with the effluent of WSP, correspondingly high levels of the same were found in the of the Marginal (TC: 1.67 $\times 10^6$ and FC: 0.29×10^6 cfu/100 ml) and Littoral (TC: 0.99×10^6 and 0.61×10^6 cfu/100; FC: 0.28×10^6 and 0.11×10^6 cfu/100 ml) Zones along the discharge route. High Coliform could be a risk that bacterial pathogens will be present in the lake water, not only on the skin of the fish, but also in their flesh and internal organs (D. Mara, 2013). Kumar et al. (2020) found that elevated levels of faecal coliforms in lake water (up to 10^4 CFU/100 mL) from hospital effluent were associated with the presence of pathogens in fish flesh and water, in agreement with Mara (2013). The study reported cases of nausea and skin irritation among swimmers. Makut and Kenneth (Makwin Danladi Makut & Kenneth, 2021) showed faecal coliform levels of 10^2-10^3 CFU/100 mL for lake water near the WSP outfalls (Makwin and Kenneth, 2021), with fish samples testing positive for coliforms in internal organs. High levels of coliforms have been associated with pathogenic bacteria (e.g., Shigella).

In general, potential contaminants derived from the effluent may pose a potential risk to the lake along the discharge route. Apart from the native inhabitants it accommodates, this part of the lake affected by the supposedly treated effluent is one of the spots where humans and their stocks interact with the same place, mainly in search of grass (Filla, Qetema, and Fish eggs or fingerlings as bait during fishing)/water and forage/water, in that order. Moreover, those people (especially children) and their livestock crossing the discharge flowing to Lake Hawassa (i.e., while the effluent is flowing in an open ditch before it finally joins the Lake) might be exposed to the constituents of the effluent.

4. Conclusions

The wastewater treatment system at Hawassa Referral Hospital (HRH) is failing. The effluent discharged into Lake Hawassa contains dangerously high levels of pollutants, including nutrients that cause eutrophication and heavy metals that pose a risk to the lake's marginal-littoral zone. The WSPs have abysmal removal efficiency. The system's failure is attributed to a poor initial design, a lack of pre-treatment, excessive sludge accumulation due to infrequent desludging, and a complete neglect of routine monitoring and maintenance by the hospital administration. Thus, the study suggested the following key recommendations:

- Redesign the WSP system to proper specifications and implement a strict schedule for desludging and maintenance.
- Introduce pre-treatment and advanced post-treatment technologies, such as constructed wetlands, to remove heavy metals.
- Transport the effluent via pipeline to the center of the lake instead of discharging it into the vulnerable shoreline.
- The hospital administration must commit to periodic monitoring to ensure effluent meets environmental standards before discharge.

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References

Abis, K. L., & Mara, D. D. (2003). Research on waste stabilisation ponds in the United Kingdom - Initial results from pilot-scale facultative ponds. Water Science and Technology, 48(2), 1–7. https://doi.org/10.2166/wst.2003.0075

Akoto, O., Ephraim, J. H., & Darko, G. (2009). Heavy metals pollution in surface soils in the vicinity of abundant railway servicing workshop in Kumasi, Ghana.

Al Kholif, M., Nurhayati, I., Sugito, Sari, D. A., Sutrisno, J., Pungut, & Mujiyanti, D. R. (2023). Removal of BOD_5 and COD from Domestic Wastewater by Using a Multi-Media-Layering (MML) System. Environment and Natural Resources Journal, 21(6), 534–544. https://doi.org/10.32526/ennrj/21/20230202

Alam, S. M. (2018). Wastewater stabilization ponds (WSP) -An ideal low- cost solution for wastewater treatment around the world. 8(1), 25–37.

Al-Sulaiman, A. M., & Khudair, B. H. (2018). Correlation Between Bod5 and Cod for Al-Diwaniyah Wastewater Treatment Plants To Obtain the Biodigrability Indices. J. Biotechnol, 15(2), 423–427. www.pjbt.org

American Public Health Association, American Water Works Association, & Water Environment Federation. (2017). Standard methods for the examination of water and wastewater (23rd ed.).

Amin, N., Foster, T., Shimki, N. T., & Willetts, J. (2024). Hospital wastewater (HWW) treatment in low- and middle-income countries: A systematic review of microbial treatment efficacy. Science of the Total Environment, 921(11), 170994. https://doi.org/10.1016/j.scitotenv.2024.170994

Amouei, A., Ghanbari, N., & Kazemitabar, M. (2010). Study of wastewater treatment system in the educational hospitals of Babol University of Medical Sciences (2009). Journal of Mazandaran University of Medical Sciences, 20(77), 77–86.

Asfaw, T., Negash, L., Kahsay, A., & Weldu, Y. (2017). Antibiotic resistant bacteria from treated and untreated hospital wastewater at Ayder Referral Hospital, Mekelle, North Ethiopia. Advances in Microbiology, 7(12), 871–886.

Awodele, O., Adewoye, A. A., & Oparah, A. C. (2016). Assessment of medical waste management in seven hospitals in Lagos, Nigeria. BMC Public Health, 16(1), 1–11. https://doi.org/10.1186/s12889-016-2916-1

Aziz, H. A., Omar, F. M., Halim, H. A., & Hung, Y.-T. (2022). Health-care waste management. In Solid waste engineering and management: Volume 3 (pp. 163–229). Springer.

Aziz, K. H. H., Mustafa, F. S., Karim, M. A., & Hama, S. (2025). Pharmaceutical pollution in the aquatic environment: Advanced oxidation processes as efficient treatment approaches: A review. Materials Advances.

Beyene, H., & Redaie, G. (2011). Assessment of waste stabilization ponds for the treatment of hospital wastewater: The case of hawassa university referral hospital. World Applied Sciences Journal, 15(1), 142–150.

Bjorkli, S.-G. (2004). The Fisheries in Lake Awassa, Ethiopia; Estimation of Annual Yield.

Blier, R., Laliberte, G., & De la Noüe, J. (1995). Tertiary treatment of cheese factory anaerobic effluent with Phormidium bohneri and Micractinum pusillum. Bioresource Technology, 52(2), 151–155.

Boyd, C. E. (2015). Water quality. Springer.

Breen, B.; Curtis, J.; Hynes, S. (2018). Water quality and recreational use of public waterways. Journal of Environmental Economics and Policy, 7(1), 1–15. https://doi.org/10.1080/21606544.2017.1335241

Carr, G. M., & Neary, J. P. (2008). Water quality for ecosystem and human health. UNEP/Earthprint.

Carraro, E., Bonetta, S., Bertino, C., Lorenzi, E., Bonetta, S., & Gilli, G. (2016). Hospital effluents management: Chemical, physical, microbiological risks and legislation in different countries. Journal of Environmental Management, 168, 185–199. https://doi.org/10.1016/j.jenvman.2015.11.021

Casas, M., & Bester, K. (2015). Biodegradation of pharmaceuticals in hospital wastewater by a hybrid biofilm and activated sludge system (Hybas). Science of the Total Environment, 530-531, 383–392. https://doi.org/10.1016/j.scitotenv.2015.05.099

Chen, Q., Li, Q., Lin, Y., Zhang, J., Xia, J., Ni, J., Cooke, S. J., Best, J., He, S., Feng, T., Chen, Y., Tonina, D., Benjankar, R., Birk, S., Fleischmann, A. S., Yan, H., & Tang, L. (2023). River Damming Impacts on Fish Habitat and Associated Conservation Measures. Reviews of Geophysics, 61(4), 1–64. https://doi.org/10.1029/2023RG000819

Christenson, L., & Sims, R. (2011). Production and harvesting of microalgae for wastewater treatment, biofuels, and bioproducts. Biotechnology Advances, 29(6), 686–702.

Daka, D., Beyene, H., & Dires, S. (2021). Spatial and temporal distribution of faecal indicators and multidrug resistant bacteria in a multiple-use freshwater lake: the case of Lake Hawassa, Ethiopia. International Journal of Infection Control, 17.

Desye, B., Belete, B., Amare Alemseged, E., Angaw, Y., & Asfaw Gebrezgi, Z. (2022). Evaluation of Waste Stabilization Pond Efficiency and Its Effluent Water Quality: A Case Study of Kito Furdisa Campus, Jimma University, Southwest Ethiopia. Scientific World Journal, 2022. https://doi.org/10.1155/2022/2800034

Di Capua, F., de Sario, S., Ferraro, A., Petrella, A., Race, M., Pirozzi, F., Fratino, U., & Spasiano, D. (2022). Phosphorous removal and recovery from urban wastewater: Current practices and new directions. Science of the Total Environment, 823, 153750. https://doi.org/10.1016/j.scitotenv.2022.153750

Dufour, A. P., Behymer, T. D., Cantú, R., Magnuson, M., & Wymer, L. J. (2017). Ingestion of swimming pool water by recreational swimmers. Journal of Water and Health, 15(3), 429–437. https://doi.org/10.2166/wh.2017.255

Edokpayi, J. N., Odiyo, J. O., Piketh, S. J., & Msagati, T. A. M. (2021). Evaluation of contaminants removal by waste stabilization ponds: A case study of Siloam WSPs in Vhembe District, South Africa. Heliyon, 7(2), Article e06227. 0al Protection, February, 1–367.

Environmental Protection Agency & United Nations Industrial Development Organization (2003). Guideline Ambient Environment Standards for Ethiopia, Environmental Protection Authority of Ethiopia (EPA), United Nations Industrial Development Organization (UNIDO), Addis Ababa (Issue August).

Escolà Casas, M., & Bester, K. (2015). Biodegradation of pharmaceuticals in hospital wastewater by a hybrid biofilm and activated sludge system (Hybas). Science of the Total Environment, 530-531, 383–392. https://doi.org/10.1016/j.scitotenv.2015.05.099

Franklin, P. A. (2014). Dissolved oxygen criteria for freshwater fish in New Zealand: A revised approach. New Zealand Journal of Marine and Freshwater Research, 48(1), 112–126. https://doi.org/10.1080/00288330.2013.827123

Gadipelly, C., Pérez-González, A., Yadav, G. D., Ortiz, I., Ibáñez, R., Rathod, V. K., & Marathe, K. V. (2014). Pharmaceutical industry wastewater: Review of the technologies for water treatment and reuse. Industrial & Engineering Chemistry Research, 53(29), 11571–11592. https://doi.org/10.1021/ie501210j

Geldreich, E. E. (1970). Applying bacteriological parameters to recreational water quality. Journal-American Water Works Association, 62(2), 113–120.

Gomez, E., Casellas, C., Picot, B., & Bontoux, J. (1995). Ammonia elimination processes in stabilisation and high-rate algal pond systems. Water Science and Technology, 31(12), 303–312.

Goyal, B., & Mohan, D. (2013). Case study on evaluation of the performance of waste stabilization pond system of Jodhpur, Rajasthan, India. Water Practice and Technology, 8(1), 95–104. https://doi.org/10.2166/wpt.2013.011

Gruber-Dorninger, C., Novak, B., Nagl, V., & Berthiller, F. (2017). Emerging mycotoxins: Beyond traditionally determined food contaminants. Journal of Agricultural and Food Chemistry, 65(33), 7052–7070.

Hagedorn, C., Robinson, S. L., Filtz, J. R., Grubbs, S. M., Angier, T. A., & Reneau Jr, R. B. (1999). Determining sources of fecal pollution in a rural Virginia watershed with antibiotic resistance patterns in fecal streptococci. Applied and Environmental Microbiology, 65(12), 5522–5531.

Ho, L., Van Echelpoel, W., & Goethals, P. L. M. (2017). Design of waste stabilization pond systems: A review. Water Research, 123, 236–248. https://doi.org/10.1016/j.watres.2017.06.071

Hodgson, I. (2008). Performance Of The Akosombo Waste Stabilization Ponds In Ghana. Ghana Journal of Science, 47(1), 35–44. https://doi.org/10.4314/gjs.v47i1.15923

Hodgson, I. O. A. (2000). Treatment of domestic sewage at Akuse (Ghana). Water SA, 26(3), 413–415.

Iwamoto, M., Hlady, G., Jeter, M., Burnett, C., Drenzek, C., Lance, S., Benson, J., Page, D., & Blake, P. (2005). Shigellosis among swimmers in a freshwater lake. Southern Medical Journal, 98(8), 774–779.

Janik-Karpinska, E., Brancaleoni, R., Niemcewicz, M., Wojtas, W., Foco, M., Podogrocki, M., & Bijak, M. (2023). Healthcare Waste—A Serious Problem for Global Health. Healthcare (Switzerland), 11(2), 1–14. https://doi.org/10.3390/healthcare11020242

Jennings, W. C., Chern, E. C., O’Donohue, D., Kellogg, M. G., & Boehm, A. B. (2018). Frequent detection of a human fecal indicator in the urban ocean: environmental drivers and covariation with enterococci. Environmental Science: Processes & Impacts, 20(3), 480–492.

Kadlec, R. H., & Wallace, S. (2008). Treatment wetlands. CRC press.

Kajitvichyanukul, P., & Suntronvipart, N. (2006). Evaluation of biodegradability and oxidation degree of hospital wastewater using photo-Fenton process as the pretreatment method. Journal of Hazardous Materials, 138(2), 384–391.

Kaloudas, D., Pavlova, N., & Penchovsky, R. (2021). Phycoremediation of wastewater by microalgae: a review. Environmental Chemistry Letters, 19, 2905–2920.

Karungamye, P., Rugaika, A., Mtei, K., & Machunda, R. (2023). Physicochemical and microbiological characterization and of hospital wastewater in Tanzania. Total Environment Research Themes, 8(February), 100075. https://doi.org/10.1016/j.totert.2023.100075

Kayombo, E. J., Uiso, F. C., & Mahunnah, R. L. A. (2012). Experience on healthcare utilization in seven administrative regions of Tanzania. Journal of Ethnobiology and Ethnomedicine, 8, 1 – 8.

Kayombo, S., Mbwette, T. S. A., Katima, J. H. Y., Ladegaard, N., & Jørgensen, S. E. (2005). Waste stabilization ponds and constructed wetlands design manual. UNEP-IETC with the Danish International Development Agency (Danida), 1–59.

KR, R. (n.d.). DeLaune RD (2008) Biogeochemistry of wetlands: science and applications. CRC Press, Boca Raton.

Kumar, V., Sikarwar, D., Majumder, A., & Kumar, A. (2020). An assessment of hospital wastewater and biomedical waste generation, existing legislations, risk assessment, treatment processes, and scenario during COVID-19. January.

Lawlor, D. W., & Tezara, W. (2009). Causes of decreased photosynthetic rate and metabolic capacity in water-deficient leaf cells: A critical evaluation of mechanisms and integration of processes. Annals of Botany, 103(4), 561–579. https://doi.org/10.1093/aob/mcn244

Lawson, E. O. (2011). Physico-chemical parameters and heavy metal contents of water from the Mangrove Swamps of Lagos Lagoon, Lagos, Nigeria. Advances in Biological Research, 5(1), 8–21.

Lencha, S. M., & Tränckner, J. (2021). Assessing the Water Quality of Lake Hawassa Ethiopia — Trophic State and Suitability for Anthropogenic Uses — Applying Common Water Quality Indices. Int. J. Environ. Res. Public Health, 18(8904). https://doi.org/10.3390/ijerph18178904

Lencha, S. M., Ulsido, M. D., & Muluneh, A. (2021). Evaluation of Seasonal and Spatial Variations in Water Quality and Identification of Potential Sources of pollution Using Multivariate Statistical Techniques for Lake Hawassa. 1–35.

Lima, A. F., dos Reis, A. G. P., Costa, V. E., & Valenti, W. C. (2024). Natural Food Intake and Its Contribution to Tambaqui Growth in Fertilized and Unfertilized Ponds. Fishes, 9(4), 139.

Liu, M., Lian, Q., Zhao, Y., Ni, M., Lou, J., & Yuan, J. (2023). Treatment effects of pond aquaculture wastewater using a Field-scale Combined Ecological Treatment System and the associated microbial characteristics. Aquaculture, 563, 739018.

Machihara, K., Oki, S., Maejima, Y., Kageyama, S., Onda, A., Koseki, Y., Imai, Y., & Namba, T. (2023). Restoration of mitochondrial function by Spirulina polysaccharide via upregulated SOD2 in aging fibroblasts. Iscience, 26(7).

Mahapatra, S., Samal, K., & Dash, R. R. (2022). Waste Stabilization Pond (WSP) for wastewater treatment: A review on factors, modelling and cost analysis. Journal of Environmental Management, 308, 114668.

Mahassen Aly, H., Adel Ibrahim, B., Mohamed Ahmed, E. S., Rasha, H., & Al Metwally Aly, Y. (2008). Dementia: clinical-neurobiochemical correlations.

Makwin Danladi Makut, O. F., & Kenneth, E. I. (2021). Bacteriological Assessment of Fish and Pond Water in Fish Farms that Use Chicken Droppings as Feeds in Keffi, Nigeria. Int. J. Adv. Res. Biol. Sci, 8(6), 1–5. https://doi.org/10.22192/ijarbs

Mara, D. (2013). Domestic wastewater treatment in developing countries. Routledge.

Mara, D. (2017). Design manual for waste stabilisation ponds in India Design Manual for Waste Stabilization Ponds in India by Duncan Mara. January 1997.

Mara, D. D. (2004). Natural sewage treatment in the UK: selection guidelines. Water and Environment Journal, 18(4), 230–234.

Mara, D. D., & Pearson, H. W. (1999). A hybrid waste stabilization pond and wastewater storage and treatment reservoir system for wastewater reuse for both restricted and unrestricted crop irrigation. Water Research, 33(2), 591–594.

McArdell, C. S., Molnar, E., Suter, M. J.-F., & Giger, W. (2003). Occurrence and fate of carbamazepine, clofibric acid, diclofenac, ibuprofen, ketoprofen, and naproxen in surface water. Environmental Science & Technology, 37(5), 1044–1051. (Note: Early reference for carbamazepine persistence, often cited in later works.)

Mersha, B. (2020). Performance Evaluation of Kotebe WasteWater Treatment Stablization Ponds in Addis Ababa, Ethiopia.

Mesdaghinia, A. R., Naddafi, K., Nabizadeh, R., Saeedi, R., & Zamanzadeh, M. (2009). Wastewater characteristics and appropriate method for wastewater management in the hospitals. Iranian Journal of Public Health, 38(1), 34–40.

Miamiliotis, A., & Talias, M. A. (2023). Healthcare workers' Knowledge about the segregation process of Infectious Waste Management in a Hospital.

Mir-Tutusaus, J. A., Parladé, E., Llorca, M., Villagrasa, M., Barceló, D., Rodriguez-Mozaz, S., Martinez-Alonso, M., Gaju, N., Caminal, G., & Sarrà, M. (2017). Pharmaceuticals removal and microbial community assessment in a continuous fungal treatment of non-sterile real hospital wastewater after a coagulation-flocculation pretreatment. Water Research, 116, 65–75. https://doi.org/10.1016/j.watres.2017.03.005

Moazzam, K. A., & Altaf, M. (2007). The potential of waste stabilization ponds effluent as a liquid fertilizer. Pakistan Journal of Botany, 39(3), 817–829.

Moga, A. M., Fitamo, D. F., & Moga, S. M. (2017). Evaluation of Hospital Wastewater Treatment and Disposal : The Case of Wolita Soddo Teaching Referral Hospital , Wolaita Zone ,. 9(5), 1–9.

Monroy-Licht, A., Carranza-Lopez, L., Parra-Guerra, A. C. D. la, & Acevedo-Barrios, R. (2024). Unlocking the potential of Eichhornia crassipes for wastewater treatment: phytoremediation of aquatic pollutants, a strategy for advancing Sustainable Development Goal-06 clean water. Environmental Science and Pollution Research, 31(31), 43561–43582. https://doi.org/10.1007/s11356-024-33698-9

Mwanyika, F. T. (2016). An assessment of efficiency of heavy metals removal by a constructed wetland at Egerton University, Kenya [Master's thesis, Egerton University].

Nkwocha, A., Ekeke, I., Kamen, F., & Oghome, P. (2013). Quality Assessment of Effluent Discharges from Vegetable oil Plant. Ethiopian Journal of Environmental Studies and Management, 6(6), 717. https://doi.org/10.4314/ejesm.v6i6.2s

Noman, E., Al-Shaibani, M. M., Bakhrebah, M. A., Almoheer, R., Al-Sahari, M., Al-Gheethi, A., Radin Mohamed, R. M. S., Almulaiky, Y. Q., & Abdulaal, W. H. (2021). Potential of anti-cancer activity of secondary metabolic products from marine fungi. Journal of Fungi, 7(6), 436.

Oliver, B. G., & Cosgrove, E. G. (1975). Metal concentrations in the sewage, effluents, and sludges of some southern Ontario wastewater treatment plants. Environmental Letters, 9(1), 75–90.

Olukanni, D. O., & Ducoste, J. J. (2011). Optimization of waste stabilization pond design for developing nations using computational fluid dynamics. Ecological Engineering, 37(11), 1878–1888.

Onu, M. A., Ayeleru, O. O., Oboirien, B., & Olubambi, P. A. (2023). Challenges of wastewater generation and management in sub-Saharan Africa: A Review. Environmental Challenges, 11(1), 100686. https://doi.org/10.1016/j.envc.2023.100686

Ortúzar, M., Esterhuizen, M., Olicón-Hernández, D. R., González-López, J., & Aranda, E. (2022). Pharmaceutical Pollution in Aquatic Environments: A Concise Review of Environmental Impacts and Bioremediation Systems. Frontiers in Microbiology, 13(April), 1–25. https://doi.org/10.3389/fmicb.2022.869332

Paerl, H. W., Gardner, W. S., Havens, K. E., Joyner, A. R., McCarthy, M. J., Newell, S. E., Qin, B., & Scott, J. T. (2016). Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients. Harmful Algae, 54, 213–222.

Penn, M.R.; Pauer, J.J.; Mihelcic, J. R. (2013). Biochemical oxygen demand. Environmental and Ecological Chemistry. In A. Sabjic (Ed.), Environmental and ecological chemistry: Vol. II (pp. 278–297). UNESCO-EOLSS.

Planas Carbonell, A. (2024). Evaluating algae biomass productivity and nutrient dynamics in a raceway pond system. Universitat Politècnica de Catalunya.

Rigotto, L., Aquino, S. F., Rigotto, J., Santos, G., Silva, L. M. L., & Santiago, A. F. (2023). Dynamics of dissolved organic matter (DOM) in waste stabilization ponds: Insights into co-treatment of sanitary sewage and landfill leachate. Journal of Water Process Engineering, 55, 104236.

Sarafraz, S., Khani, M. R., & Yaghmaeian, K. (2007). Quality and quantity survey of hospital wastewaters in Hormozgan province.

Scholes, E., Verheyen, V., & Brook-Carter, P. (2016). A review of practical tools for rapid monitoring of membrane bioreactors. Water Research, 102, 252–262.

Shaheen, M. N. F., Elmahdy, E. M., Rizk, N. M., Abdo, S. M., Hussein, N. A., Elshershaby, A., Shahein, Y. E., Fawzy, M. E., El-Liethy, M. A., Marouf, M. A., Abdel-Gawad, F. K., Hu, A., & Gad, M. (2024). Evaluation of physical, chemical, and microbiological characteristics of waste stabilization ponds, Giza, Egypt. Environmental Sciences Europe, 36(1). https://doi.org/10.1186/s12302-024-00965-y

Shilton, A., Pratt, S., Drizo, A., Mahmood, B., Banker, S., Billings, L., Glenny, S., & Luo, D. (2005). 'Active'filters for upgrading phosphorus removal from pond systems. Water Science and Technology, 51(12), 111–116.

Shroff, P.; Vashi, R.T.; Champa neri, V.A.; Patel, K. K. (2015). Correlation Study among water quality parameters of groundwater of Valsad District of south Gujarat (India). Journal of Fundamental and Applied Sciences ISSN, 151, 1–10. https://doi.org/10.4314/jfas.v7i3.3

Silva, J. A. (2023). Wastewater Treatment and Reuse for Sustainable Water Resources Management: A Systematic Literature Review. Sustainability (Switzerland), 15(14). https://doi.org/10.3390/su151410940

Silva, S. A., De Oliveira, R., Soares, J., Mara, D. D., & Pearson, H. W. (1995). Nitrogen removal in pond systems with different configurations and geometries. Water Science and Technology, 31(12), 321–330.

Sinn, J., & Lackner, S. (2020). Enhancement of overloaded waste stabilization ponds using different pretreatment technologies: A comparative study from Namibia. Journal of Water Reuse and Desalination, 10(4), 500–512. https://doi.org/10.2166/wrd.2020.021

Swietlicki, E., Puri, S., Hansson, H.-C., & Edner, H. (1996). Urban air pollution source apportionment using a combination of aerosol and gas monitoring techniques. Atmospheric Environment, 30(15), 2795–2809.

Taslimi, M., Batta, R., & Kwon, C. (2020). Medical waste collection considering transportation and storage risk. Computers and Operations Research, 120, 104966. https://doi.org/10.1016/j.cor.2020.104966

Thakur, M., Chandel, M., Rani, A., Sharma, A., & Pathania, D. (2023). Chemical methods for the treatment of biomedical hazardous waste. In Waste Management and Resource Recycling in the Developing World (pp. 521–541). Elsevier.

Udofia, E. A. (2016). Healthcare waste management in Africa [Thesis or report, School of Public Health, College of Health Sciences, University of Ghana].

United States Environmental Protection Agency (USEPA). (1986). Quality Criteria for Water 1986. Water EPA 440/5-86-001, May 1, 477.

Varma, M., Gupta, A. K., Ghosal, P. S., & Majumder, A. (2021). A review on performance of constructed wetlands in tropical and cold climate: Insights of mechanism, role of influencing factors, and system modification in low temperature. Science of the Total Environment, 755, 142540.

Verlicchi, P., Galletti, A., Petrovic, M., & Barceló, D. (2010). Hospital effluents as a source of emerging pollutants: An overview of micropollutants and sustainable treatment options. Journal of Hydrology, 389(3-4), 416–428. https://doi.org/10.1016/j.jhydrol.2010.06.005

Vijverberg, J., Dejen, E., Getahun, A., & Nagelkerke, L. A. J. (2012). The composition of fish communities of nine Ethiopian lakes along a north-south gradient: Threats and possible solutions. Animal Biology, 62(3), 315–335. https://doi.org/10.1163/157075611X618246

Wang, M., Zhang, D., Dong, J., & Tan, S. K. (2018). Application of constructed wetlands for treating agricultural runoff and agro-industrial wastewater: a review. Hydrobiologia, 805(1), 1–31. https://doi.org/10.1007/s10750-017-3315-z

Wang, T., Zhu, B., & Zhou, M. (2019). Ecological ditch system for nutrient removal of rural domestic sewage in the hilly area of the central Sichuan Basin, China. Journal of Hydrology, 570(January), 839–849. https://doi.org/10.1016/j.jhydrol.2019.01.034

Yazie, T. D., Tebeje, M. G., & Chufa, K. A. (2019). Healthcare waste management current status and potential challenges in Ethiopia: A systematic review. BMC Research Notes, 12(1), 1–7. https://doi.org/10.1186/s13104-019-4316-y

Zhang, B., Ning, D., Yang, Y., Van Nostrand, J. D., Zhou, J., & Wen, X. (2020). Biodegradability of wastewater determines microbial assembly mechanisms in full-scale wastewater treatment plants. Water Research, 169, 115276.

Ziarati, P., Mokhtarzadeh, M., Vambol, V., Vambol, S., Sawicka, B., Mahmoud, A. E. D., & Khan, N. A. (2022). Bioremediation of pharmaceutical effluent by food industry and agricultural waste biomass. Hospital Wastewater Treatment, 53.