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Sewage Treatment by Kolkata's Natural Wetland System

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ABSTRACT

The metropolis of Kolkata stands uniquely positioned to implement a natural sewage treatment paradigm through the utilization of waste stabilization ponds, specifically within the East Kolkata Wetlands (EKW). These shallow oxidation ponds harness solar irradiation and algae bacteria symbiotic processes to effectively treat incoming sewage. Concurrently, nutrient-rich effluents are assimilated through fish production, converting available nutrients into protein—a hallmark of nature-based treatment. A portion of raw sewage is used to cultivate a chunk of vegetables before treatment in fish ponds, and the reclaimed water after treatment is used for vegetable and paddy cultivation downstream. This investigation explains the delineation of a sewage flow system to EKW, a Ramsar-designated site. Substantively, it offers quantitative insights into the sewage volumes and quality undergoing treatment. The sewage flow is higher in the winter months (909.07 MLD) compared to the summer months (709.34 MLD). In general, the sewage from the Kolkata city flowing to the EKW is moderately polluted. Extensive scrutiny of sewage from pond inlets and outlets serves as a quantitative metric for evaluating treatment efficacy. EKW efficiently treats the sewage, demonstrating 59.1% Biological Oxygen Demand (BOD) removal and a 99.28% reduction in fecal coliform. The natural treatment system excels in removing ammoniacal nitrogen (80.38%) and phosphate (90%). The treated water's quality along the EKW boundary, culminating at the Kulti Gong River discharge point, was systematically assessed. Analytical findings indicate that all measured concentrations in the treated water adhere to prescribed inland surface water discharge standards prescribed by the Central Pollution Control Board, India, barring a marginal elevation in BOD during winter. Evidently, the EKW system adeptly manages substantial sewage volumes, fostering efficient treatment while concurrently facilitating resource recovery through fish production, yielding economic dividends. Despite its substantial land footprint, preserving this inherently sustainable wastewater management paradigm is imperative.

INTRODUCTION

India's wastewater is predominantly composed of domestic and municipal effluents, accounting for approximately 75% of the total volume. Globally, only about 20% of wastewater produced receives proper treatment (UN-Water 2012, WWAP 2017). In developing countries, sewage treatment plants have varying levels of compliance. Urban wastewater in India has been estimated as 72,368 MLD and only 28% (20,236 MLD) is treated (Niti Aayog 2022). Consequently, a significant portion of the wastewater, approximately 72%, is left untreated and could potentially be discharged into rivers, lakes, or groundwater sources. According to the Central Pollution Control Board (CPCB), an entity operating under the Ministry of Environment, Forests & Climate Change (MoEFCC) of the Government of India, approximately 39% of sewage treatment plants fail to meet the overall standards outlined in the Environmental (Protection) Rules for releasing effluents into water bodies (CPCB 2021).

The city of Kolkata (206.08 sq. km) generates a huge volume of sewage as it has a population of more than 4.5 million (Census of India 2011) along with a floating population of 6 million per day (KMC 2022). The sewage of this city is treated in the wetlands in an eco-friendly manner, along with the cultivation of fish in the sewage-fed ponds. A portion of the sewage, before entering the fish pond area of EKW, is also used for irrigation in the vegetable fields. In addition to this, the treated water is reused for cultivating edibles like paddy and vegetables for the city. Reusing treated wastewater is an important approach to water conservation. The utilization of sewage for irrigating vegetables and other short-term crops has been documented in developing nations across Africa and southern Asia (Vymazal 2010). The city of Kolkata also has five municipal sewage treatment plants (STPs), namely, Baghajatin, Bangur, Gardenr Reach, Hatisur and Keorapukur. However, their treatment capacity is much less than the sewage generated every day from the city. The total installed capacity of these STPs is 179 MLD. The treated water from these STPs partially complies with the standards.

Wetland systems are recognized as a practical and economical method for treating wastewater on-site. These systems are known for their low energy consumption and environmentally friendly nature (Cui et al. 2020). Many researchers have studied the biogeochemical, hydrological, biological, and cultural services of wetlands in various countries (Chen et al. 2009, Geber & Bjorklund 2002, Moreno et al. 2007). Along with these services, wetlands have been used for wastewater treatment for a long time (Stainbridge 1976). Shallow wetlands, which work as oxidation ponds, are used to treat water, specifically in warm climatic areas (Butler et al. 2017). Wetlands, despite their mechanical simplicity, exhibit a profound biological complexity that empowers them to accomplish significant levels of treatment (Kadlec & Wallace 2009). By effectively reducing suspended solids, toxic organic substances, nutrients, heavy metals, and bacteria, wetlands play a pivotal role in enhancing the quality of wastewater.

Moreover, these systems hold great potential for addressing climate change and reducing greenhouse gas emissions (Gude et al. 2013). It has been proven that Constructed wetlands can efficiently decrease micro-pollutants in municipal sewage (Breitholtz et al. 2012). Constructed wetlands are highly efficient in treating concentrated livestock wastewaters, exhibiting an average removal rate of 65% for BOD_5, 53% for TSS, 48% for NH_4^+-N, 42% for Total Nitrogen, and 42% for Total Phosphate (Knight et al. 2000). The reduction of pollutants levels is achieved mainly due to algae bacteria symbiosis. The shallow wetlands (30-45 cm depth) have a high algal growth rate, which maintains dissolved oxygen levels throughout the pond (USEPA 2011). The photosynthetic activity occurring during the day ensures a steady supply of oxygen, while the gentle wind that enters the area facilitates the aeration of the shallow pond water (Davis & Cornwell 2008). These shallow aerobic ponds, characterized by their low depth, offer an excellent solution for sewage treatment as they possess a high capacity for removing organic substances (BOD). Operating within a detention time of 2–6 days and a BOD loading rate ranging from 112 to 225 kg.1000 m^{-3} per day, these ponds achieve an impressive 95% efficiency in BOD removal (USEPA 2011). The utilization of algae primarily facilitates the treatment process in maturation ponds. These ponds remove fecal coliform, pathogens, and nutrients along with the BOD (Varon & Mara 2004). Considered one of the most productive ecosystems worldwide, wetlands offer vital support to a wide variety of aquatic and semiaquatic organisms (Cherry 2011, Dalu et al. 2017, Bai et al. 2019, Bird et al. 2019).

The utilization of wastewater for aquaculture has been acknowledged for a considerable time in Asia, with a history spanning several centuries. Subsequently, the utilization of municipal wastewater has experienced significant growth since the 1950s. Since the late 19^{th} Century, wastewater-fed aquaculture has been extensively researched by scientists in Germany (Prein 1990). Whereas, in India, it commenced much earlier, in 1879, by a local landlord and fish farm proprietor, Bhabanath Sen, who let Kolkata's sewage into his fishponds (Bunting et al. 2010). The Kolkata waste water fish pond system offers the benefit of not only fish production but also the enhancement of the quality and the mitigation of pathogens in the sewage. However, a detailed study on how the sewage of Kolkata is entering the EKW and the quantity of sewage was hardly assayed.

Along with this, literature on the comparison of sewage quality at the incoming channels with the treated water coming out from the ponds is scanty. The treatment capacity of ponds of EKW has become crucial to keep the wetlands working as a natural sewage treatment system. The objectives of the study were to measure the volume and quality of incoming sewage received by the EKW and to estimate the treatment efficacy of the system.

STUDY AREA

The investigated site EKW is located between 22°25' to 22°40' North and 88°20' to 88°35' East (Ramsar convention 1971) within the districts of South 24 Parganas. North 24 Parganas, West Bengal, India (Fig. 1). It covers rural/panchayat areas and also peri-urban areas lying within Kolkata and Bidhannagar Municipal Corporations of West Bengal. The total area of the wetlands is 12,500 hectares. Among the total area, a substantial water body-oriented area (fish farming) is 5852.14 hectares, along with an agricultural area (paddy and floriculture) of 4718.56 ha, a productive farming area (vegetable farming) of 602.78 ha, and an urban/rural settlement area of 1326.52 ha (Ghosh 2005). The EKW, selected as a Ramsar site in 2002, comprises sewage-carrying channels and an ensemble of interconnected oxidation ponds.

The unique hydraulic nature of these ponds is they are neither lotic nor lentic. The inflow of sewage into the ponds occurs through inlet channels in batches, and the outflow is likewise regulated. In the large ponds (40-45 hectares), the sewage enters continuously, and the pond acts as a lotic system (Ray Chaudhuri & Thakur 2006). The ponds of EKW are shallow with a depth of about 45-60 cm so that the sunlight can reach up to the bottom. This allows algal growth, which increases the dissolved oxygen (DO) level in the water (USEPA 2011). Bacteria thrive there by taking up the DO and breaking down the organics. The degradation of sewage occurs in the ponds of EKW as they act as waste stabilization ponds (Ghosh 2005).

In 7-8 days of retention time, the sewage is purified (Sarkar et al. 2016) because it takes only 3-4 days for the anoxic water to become clear and oxic (Sarkar et al. 2014). This form of treatment is very effective for the removal of pathogens, including viruses, from wastewater. The prudent usage of the water to cultivate fish in the sewage ponds was discovered by the fishermen of this area as they have gathered experience about the particular timing of the introduction of sewage into these ponds. Fish cultivated in the ponds help in resource recovery by utilizing the available nutrients and converting them into protein for human consumption. The problem of eutrophication due to high algal growth is controlled by cultivating fish in the ponds. Water quality in wastewater-fed ponds is evaluated by examining the color of the water, the extent to which light can penetrate it, and the behavior of fish surfacing after dawn when the concentration of DO in the pond is at its lowest point during the night. The presence of green coloration and limited light penetration indicate good water quality, as they suggest the presence of an adequate number of protein-rich plankton for fish to consume. Feeding of sewage is done at regular intervals to maintain the organic load of the water. The treated water is removed from the pond through the outlets, which fall into various interconnecting canals. These canals carry the treated water to the SWF canal. A part of the treated water is also utilized for other non-potable purposes, viz., growing vegetables and paddy (Ghosh 2005, Ghosh & Sen 1987, Bose 1944).

Treatment of sewage is a continuous process in the ponds of EKW. However, ponds must be preserved and managed for efficiency. At the time when the pond bottom is filled with excess sludge/sediment, it is cleaned following different management practices depending on the size of the pond. For small to medium-sized ponds (up to 4 acres), the first step is to remove the water, which is done mostly during

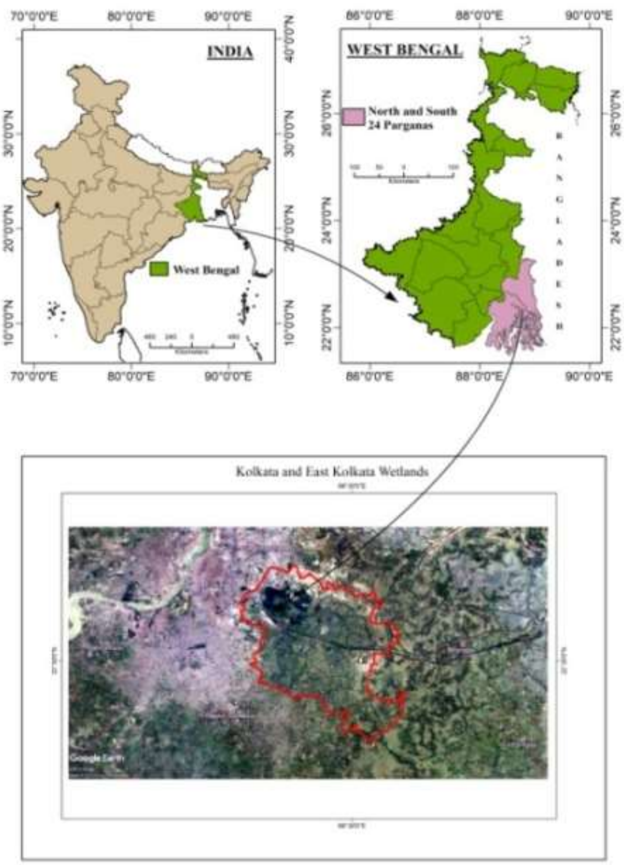

Fig. 1: Geographical location of the study area.

winter months (November to March). The sediment is then thoroughly dried, turned over, and further dried. Then, lime (calcium hydroxide) and Mahua oil cake, a natural fertilizer rich in macro and micronutrients, are added. The utilization of lime in the pond preparation process leads to a substantial decline of 96-99% in fecal coliform levels (Pradhan et al. 2008). After that, the sewage is let into the pond for about 30-45 cm depth or more, depending on the size of the pond. After that, a sedimentation time of 15-21 days is allowed and the water changes its color from blackish to greenish due to the growth of algae, and the water turns clearer as the DO level rises substantially. The entire pond preparation process takes 30-45 days. From India, only EKW managed and maintained by fishermen and farmers, was identified among one of the 17 tutorial wetland ecosystems in the world by the Ramsar Convention in 1993, as reported in their wise use project.

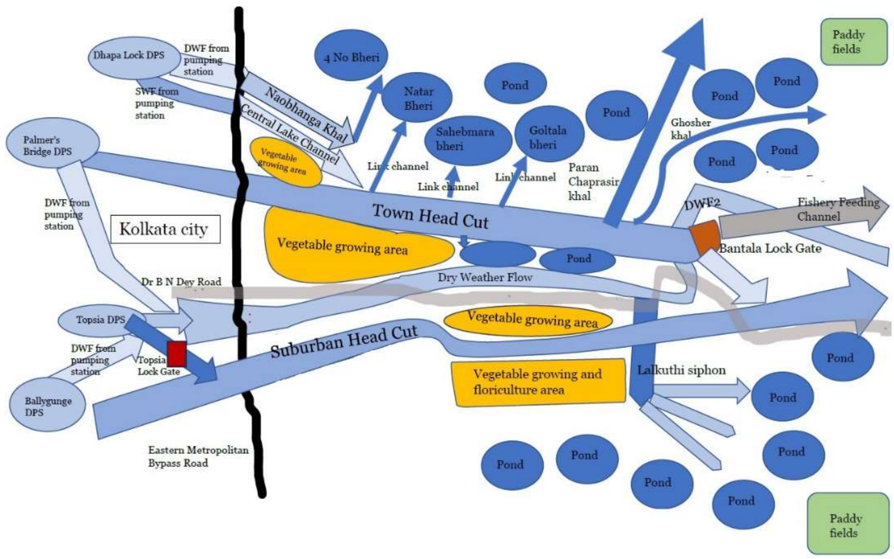

Fig. 2: Sewage flow pattern from Kolkata into EKW.

Table 1: Details about sewage-carrying channels connected to EKW from the city of Kolkata.

Name of main sewage channel	Origin of sewage carried	Name of distributary sewage canals	Location of ponds served by the channel
Naobhanga *Khal* (NBK)	Sewage from Dhapa Lock DPS		Upstream of Bantala Lock Gate
Central Lake Channel (CLC)	Sewage from Dhapa Lock DPS		Upstream of Bantala Lock Gate
Town Head Cut (THC)	Sewage originating from Dhapa Lock and Palmer's Bridge DPS	1. Natar bheri link *Khal* 2. Sahebmara link *Khal* 1 3. Sahebmara link *Khal* 2 4. Goltala link *Khal* 5. Khanaberia *Khal* 6. Paran Chaprashir *Khal* 7. Ghosher *Khal*	Upstream and downstream of Bantala Lock Gate
DWF	Sewage from Palmer's Bridge, Topsia, and Ballygunge DPS	1. Bidyadhari 1 *Khal* 2. Bidyadhari 2 *Khal* 3. Bidyadhari 3 *Khal*	The right side of Dr. B.N. Dey road via Lalkuthi siphon; southern part of EKW
Suburban Head Cut and SWF	Stormwater flow of Ballygunge DPS with link channel from Topsia as a tributary		
Fishery Feeding Canal (FFC)	Sewage of THC from Bantala Lock Gate		The left side of Dr. B.N. Dey Road, up to the central point of the EKW boundary

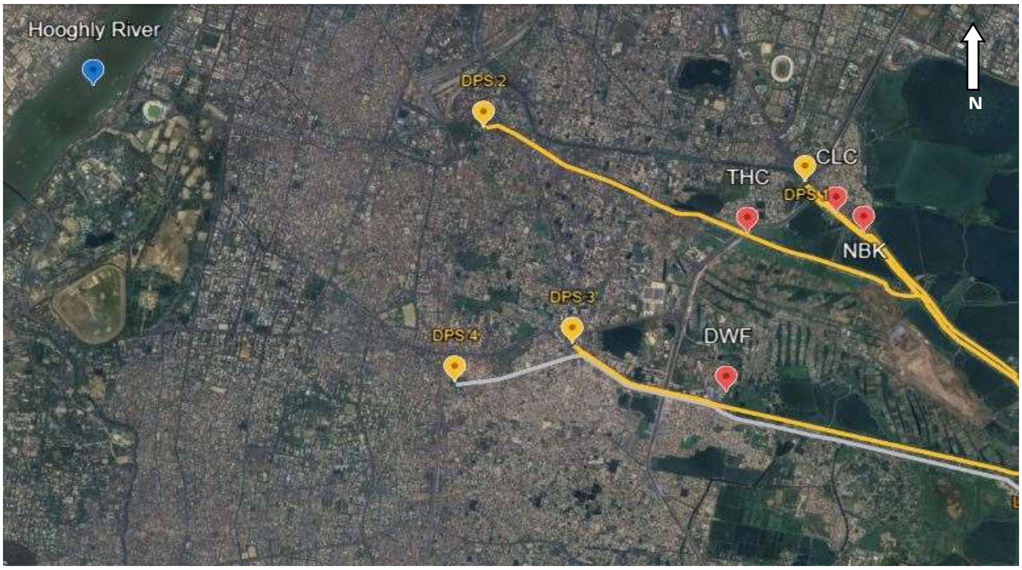

Fig. 3: Location of volume flow measurements in incoming sewage channels (marked red).

SEWAGE FLOW TO EKW

Few reconnaissance surveys were conducted, and it was found that the sewage generated from the city was carried by a network of sewage-carrying channels that were initiated from four sewerage and drainage pumping stations (DPS), namely Dhapa Lock (DPS 1), Palmer's Bridge (DPS 2), Topsia (DPS 3), and Ballygunge (DPS 4) (Fig. 2 and 3). From the pumping stations, the sewage was pumped out with great force through outfall channels that carry the sewage to the wetlands for distribution. Each of the four DPS has two channels: dry weather flow (received sewage uniformly throughout the year) and stormwater flow (received sewage more heavily during the monsoon). These drainage-pumping stations pump the sewage to the dry weather flow and stormwater flow channels according to the sewage availability throughout the year.

The two channels that start from Dhapa Lock DPS are called Central Lake Channel (CLC) and Naobhanga *Khal* (NBK; canals are known as *khal* in the local language). NBK and CLC provide water to the ponds located on the northern side of the EKW area. The surplus water of CLC joins the stormwater flow channel of Palmer's Bridge DPS, which is known as Town Head Cut (THC). The ponds at the left side of THC receive sewage from it through seven distributary *khals*. The left-over sewage reaches the end of the THC channel at Bantala, Kolkata. It is distributed down the Southern side through a set of ten regulator gates at Bantala, known as Bantala Lock Gate, located on the left side of Dr. B. N. Dey Road. From the lock gate, the Fishery Feeding Canal (FFC) begins, which serves the northern EKW ponds downstream of the Bantala lock gate. The sewage of THC is channeled by gravity flow into the FFC.

The dry weather flow channel of Palmer's Bridge DPS meets the dry weather flow channels of Topsia DPS and Ballygunge DPS, and combined, these channelize their sewage into the main Dry Weather Flow (DWF) channel. The DWF canal, while traveling downstream, provides sewage to the ponds located on the southern part of EKW (right side of Dr. B. N. Dey Road) through a siphon called the Lalkuthi siphon. The stormwater flow of Ballygunge DPS is known as Suburban Head Cut (SHC), and a short connecting channel (stormwater flow channel of Topsia DPS) acts as a tributary of SHC. This channel is named the Storm Weather Flow (SWF) after the Bantala lock gate. The FFC, DWF, and SWF travel parallelly. The DWF and SWF fall into the river Kulti Gong, which is about 27 km away from the Bantala Lock Gate (Drainage Enquiry Committee 1945). It has also been observed that sewage water is utilized for watering the rice and vegetable fields situated in the eastern region of the EKW area. Table 1 and Fig. 2 show the details of the channels carrying sewage to EKW.

The flow of sewage to the EKW was estimated at NBK (near 19-bigha field), CLC (near Tapuriaghata Boy's Sporting Club), THC_{TB} (under CESC Truss Bridge at Metropolitan bus stop), and DWF_{AP} (located at Auropota) as these four are the incoming sewage channels for all the ponds of EKW (Fig. 3). Samples were collected from each channel during winter and summer spanning January 2023 to October 2023 with the aid of the Acoustic Doppler Current Profiler (ADCP) along the cross-section of the channels

Fig. 4: A sewage channel to EKW.

(Fig. 4). The ADCP measures the instantaneous volume flow in $m^3 \cdot s^{-1}$. So, flow was measured multiple times in each canal to get the average volume flow.

It was observed that there were seasonal variations in the combined flow from the four main canals - during winter, it reached 909.07 million liters per day (MLD), whereas during summer, it was 709.34 MLD. After calculating the total average flow of the sewage-carrying channels, the percentage distribution of sewage by each channel was determined.

Table 2: Volume of sewage carried by the channels.

Sewage channels	Winter		Summer	
	MLD	Percentage	MLD	Percentage
NBK	110.59	12	72.00	10
CLC	191.19	21	130.72	18
THC_{TB}	316.29	35	41.59	6
DWF_{AP}	291.00	32	465.03	66
Total Flow	909.07	100	709.34	100

Table 2 provides the average daily flow of the four sewage channels and also as percentage. Notably, THC_{TB} exhibits the highest average flow in winter (316.29 MLD; 35%; Fig. 5a), and DWF_{AP} shows the highest average flow in summer (465.03 MLD; 66%; Fig. 5b).

Physicochemical and Microbiological Quality of Incoming Sewage

Sterile containers were used for bacteriological tests and clean polyethylene terephthalate (PET) bottles were used (with and without preservatives) for other tests. The bottles were rinsed three times taking water from the sampling site before being utilized for sample collection. Subsequently, water samples from each site (collected at various times on the same day) were combined to create composite samples. These collected samples were then placed in an icebox and transported to the laboratory for analysis.

pH and turbidity were measured on-site using portable meters. Alkalinity, chloride, Total Solids (TS), Total

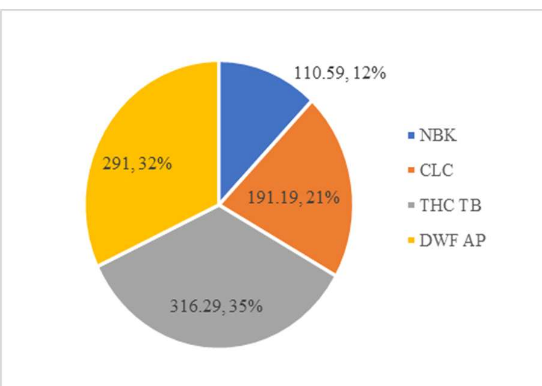

Fig. 5a: Percentage of sewage flow in winter.

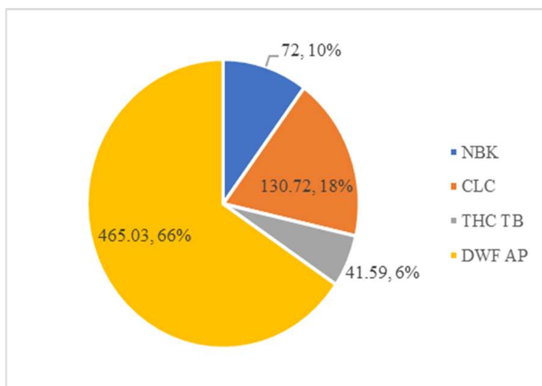

Fig. 5b: Percentage of sewage flow in summer.

Suspended Solids (TSS), Total Dissolved Solids (TDS), Total Volatile solids (TVS), Volatile Suspended Solids (VSS), phosphate, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Kjeldahl Nitrogen (TKN), total coliform and *E. coli* were measured following standard methods as outlined by APHA (2017). Ammoniacal nitrogen (NH_4^+-N) and nitrate were measured using an ion-selective electrode, and Total Organic Carbon (TOC) was measured using a TOC analyzer. All the reagents and chemicals utilized in the current investigation were of analytical quality. Deionized water was employed for all the procedures of preparation and dilution during the study.

Nine locations were chosen to estimate the physico-chemical and microbiological parameters present in the sewage throughout the canals, namely NBK, CLC, THC_{TB}, and DWF_{AP}. THC at Khanaberia (THC_{KB}; as it is near the Dhapa solid waste dumping site, to investigate potential contamination from the leachate), starting point of FFC_B (at Bantala lock gate) and Lalkuthi siphon (LKTS), FFC_{KT} (FFC at Kantatala; located at the edge of the EKW border) and DWF_{KT} (DWF at Kantatala) (Fig. 6). Samplings were done in winter (Jan-Feb 2023) and in summer (May-June 2023).

The first four locations were before sewage entered into any production activity (near the western boundary of the EKW area), the subsequent three locations are inside the EKW area (near the Bantala lock gate), and the remaining two are located at the EKW eastern boundary (towards the Kulti river). The reduction percentage was calculated by taking into account the average value found at the initial four locations and the average value of the final two locations, including both seasons.

The pH values ranged from 7.05 to 7.56 in all channels, including both seasons. The measured pH values were within the discharge limit of 6.5 to 9.0 laid by CPCB (1993) (Fig. 7). The pH levels were a little higher in summer than in winter, though there were no significant differences across all the channels that were measured. During winter, the levels of Total Solid (TS) and Total Suspended Solid (TSS) tend to be higher due to the reduced volume of water in the channels, except for THC_{KB} and FFC_B (Fig. 8). The range of TSS concentration in all the nine locations was between 170 to 766 $mg.L^{-1}$ in the winter. In contrast, in the summer, the range was found in between 126 to 687 $mg.L^{-1}$. The average value of TS in the first four locations (NBK, CLC, THC_{TB}, and DWF_{AP} before delivering sewage to the ponds) was 600 $mg.L^{-1}$, taking into account both seasonal values. The average seasonal value (considering both seasons) of TS was reduced to 457.5 $mg.L^{-1}$ in THC_{KB}, FFC_B, and LKTS. The FFC_{KT} and DWF_{KT}, at the final point of EKW, had 177.5 $mg.L^{-1}$ of TS on an average value covering both seasons. This shows that the settleable portion of the TS accumulates at the bottom of the channels and ponds, necessitating periodic cleaning to ensure proper function. Meanwhile, the range of TSS was found to be between 28 to 68 $mg.L^{-1}$ in winter and 21 to 52 mg.Lv in summer in the first four locations. The average value of TSS in these four channels was 40.86 $mg.L^{-1}$ and the TSS is much lower than the prescribed limit (100 $mg.L^{-1}$) of discharge in inland surface water (CPCB 1993). However, the average TSS concentration in the THC_{KB}, FFC_B, and LKTS was 42.75 $mg.L^{-1}$, and the average TSS of FFC_{KT} and DWF_{KT} was 32 $mg.L^{-1}$ (including both seasons), which was within the discharge limit. The reduction percentages for TS and TSS were 70.4 and 21.7, respectively. In the winter season, the average concentration of COD in the first four locations (NBK, CLC, THC_{TB}, and DWF_{AP} before delivering sewage to the ponds) was recorded at 158.75 $mg.L^{-1}$, while in the summer season, the average concentration dropped to 88.25 $mg.L^{-1}$ with a range of 76 to 248 $mg.L^{-1}$ in winter and 74 to 110 $mg.L^{-1}$ in summer. The THC_{KB}, FFC_B, and LKTS had a range of 213 to 266 $mg.L^{-1}$ of COD in winter and 38 to 88 $mg.L^{-1}$ in summer. The final sampling locations (downstream of EKW) of FFC_{KT} and DWF_{KT} had a COD between 26 to 165 $mg.L^{-1}$, covering both seasons. The average COD in all the locations in both seasons was 123.22 $mg.L^{-1}$. Despite these variations, the concentration of COD at the final locations remained within the discharge limit (250 $mg.L^{-1}$ for inland surface water as laid by CPCB 1993) during both seasons. COD shows much lower levels in summer in all the channels (Fig. 9). The reduction percentage is 34 from the initial point to the final point. Similarly, the average BOD concentration in the winter season was measured at 43 $mg.L^{-1}$. In contrast, in the summer season, it decreased to 22.75 $mg.L^{-1}$ across the first four locations, with a range of 19 to 66 $mg.L^{-1}$ in winter and 20 to 28 $mg.L^{-1}$ in summer. However, the concentration of BOD at the middle portion of the channels, i.e., $THC_{KB,}$ FFC_B, and LKTS, lies between 9.4 to 70 $mg.L^{-1}$, including both seasons, with an average of 38.4 $mg.L^{-1}$. The FFC_{KT} and DWF_{KT} (the final locations downstream of EKW) have an average of 35 $mg.L^{-1}$ of BOD in winter and 15 $mg.L^{-1}$ in summer. This observation confirms that microbes function more efficiently in summer (concentration is within the discharge standards; CPCB 1993), and sewage treatment is carried out partially throughout the entire stretch of the sewage channels. However, it is worth noting that most of the BOD values measured in winter slightly exceeded the discharge limit of 30 $mg.L^{-1}$ (CPCB 1993; Fig. 9) due to the less activity of microbes at lower temperatures. In the first four channels, the average concentrations of phosphate and nitrate were 0.89 $mg.L^{-1}$ and 0.53 $mg.L^{-1}$, respectively, when considering both seasons. The range was between 0.65 -1.17 and 0.41-0.65 $mg.L^{-1}$ for phosphate and nitrate, respectively, in the first four sites. In the mid-section, at THC_{KB}, FFC_B, and LKTS, the average concentration of phosphate and nitrate were 0.75 and 0.83 $mg.L^{-1}$, considering both seasons. At the final locations (downstream of EKW) at DWF_{KT} and $FFC_{KT,}$ the average seasonal concentrations were 0.47 and 0.30 $mg.L^{-1}$. These concentrations were found to be far below the discharge limit (CPCB 1993) for both phosphate (5 $mg.L^{-1}$) and nitrate (10 $mg.L^{-1}$) in all the nine samples measured (Fig. 10). The reduction percentages were 47.31 and 43.01 for phosphate and nitrate, respectively. On the other hand, the average concentration of TKN was significantly higher in the winter compared to the summer in all the locations. The average TKN of the first four locations was 18.36 (range 4.3 -37.8) $mg.L^{-1}$, including both seasons (Fig. 11). The THC_{KB}, FFC_B, and LKTS had an average of 12.6 (range 3.6-21.5) $mg.L^{-1}$ and the average of FFC_{KB}, and DWF_{KB} was 9.45 $mg.L^{-1}$ including winter and summer. The measured values of TKN in all the samples were found to be much lower than the discharge limit of 100 $mg.L^{-1}$ (CPCB 1993). The reduction percentage was 48.39.

During the summer season, it has been observed that the levels of E. coli are significantly higher in all the measured channels. The average count of E. coli during summer at the first four channels was much greater compared to winter, reaching 1190 on an average (range 920-1500) MPN.100 mL^{-1}, as microbial growth tends to accelerate in warmer temperatures (Fig. 12). The average count of E. coli at the first four channels in the winter was 598 on an average (range 430-920) MPN.100 mL^{-1}. The THC_{KB}, FFC_B, and LKTS have a count of 757 and 380 MPN.100 mL^{-1} in the summer and winter seasons, respectively, at an average. Furthermore, the concentration of E. coli in FFC_{KT} and DWF_{KT} were 49 and 705 MPN.100 mL^{-1} at an average considering both seasons. It has been observed that the E. coli count was within the discharge limit for STP of CPCB (2017; 1000 MPN.100 mL^{-1}) at FFC_{KT} and DWF_{KT} in both winter and summer.

It has been observed that except BOD (in winter) all other values of FFC_{KT} and DWF_{KT} were within the discharge limit. Taking into account the fact that the water from these channels may be lowered further while traveling downstream to the final discharge point, which is approximately 27 Km away at the Kulti Gong River, the microbes will persistently break down the organic matter along the entire pathway. In general, the sewage from the Kolkata city flowing to the EKW is moderately polluted (Fig. 7-12). EKW is providing a natural system of treatment of sewage in the city, protecting the health of the receiving river Kulti Gong.

SEWAGE TREATMENT IN EKW PONDS

To determine the extent of sewage treatment by the ponds located in the EKW area (Fig. 13), four representative ponds were selected according to size and location, covering three seasons (pre-winter, winter, and pre-summer of 2022; Table 3). Among the four, two are situated on the left side of the DWF canal and receive sewage from THC (via a sewage distributing canal named Ghosher *Khal*), and the other two are located on the right side of the DWF canal and obtain water from Lalkuthi siphon by a connected sewage distribution canal. Dakshin Gorumara Bheri (pond 4) is the largest among the four ponds and Bantala 2 no. Bheri (pond

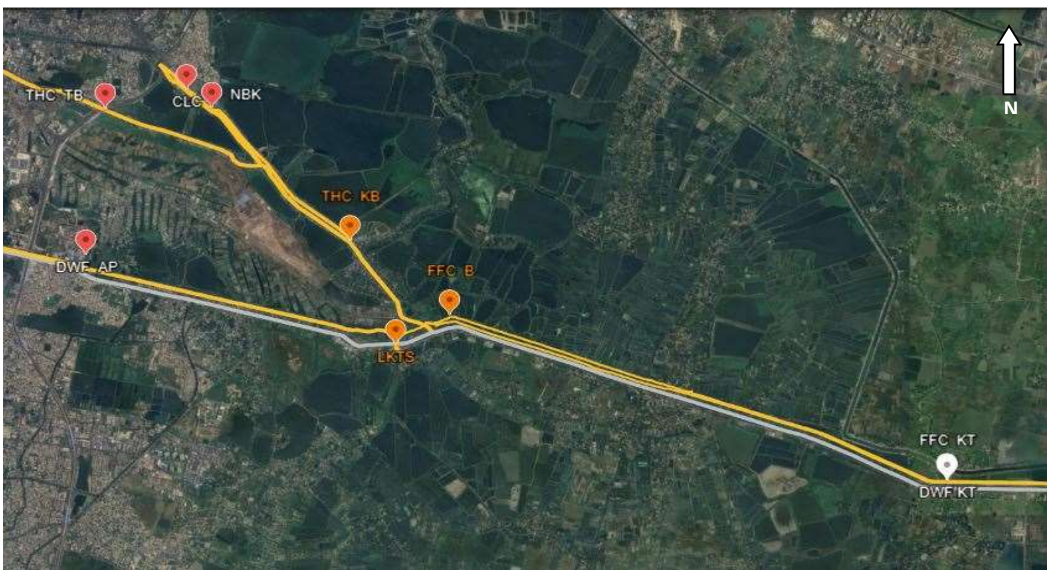

Fig. 6: Location of sampling sites for physicochemical and microbiological analysis throughout the sewage channels.

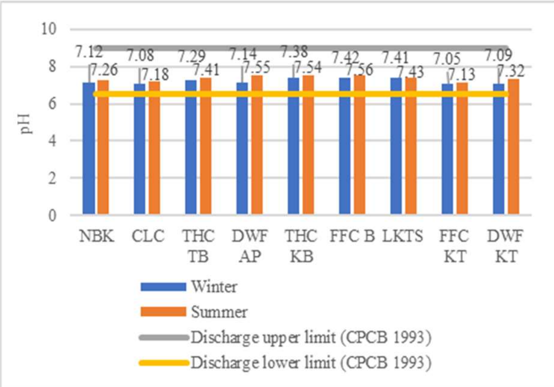

Fig. 7: pH at the sewage samples.

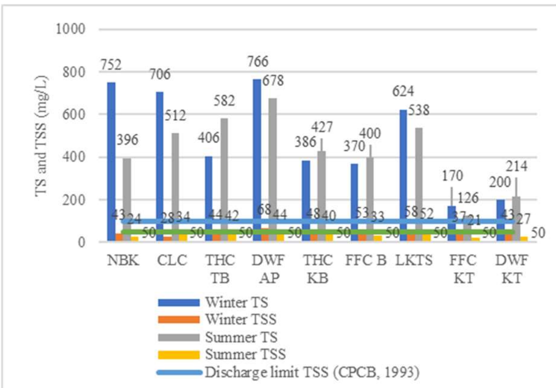

Fig. 8: TS and TSS at the sewage samples.

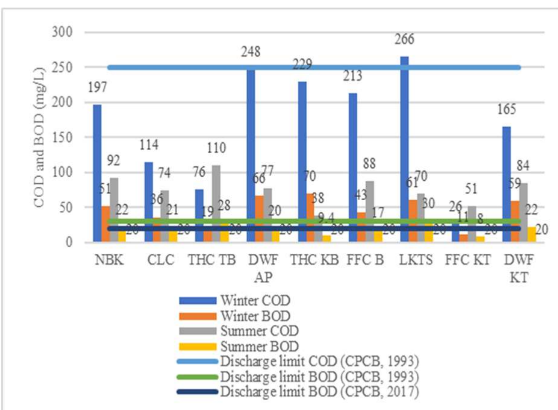

Fig. 9: COD and BOD at the sewage samples.

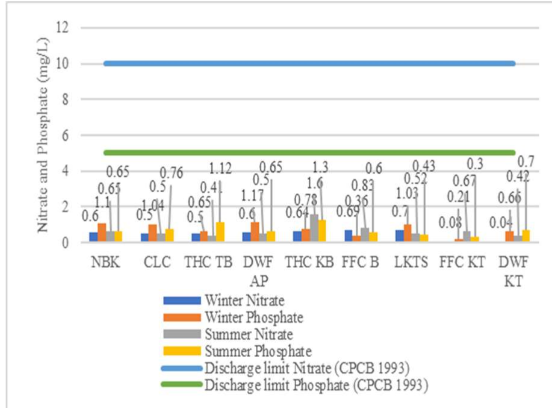

Fig. 10: Nitrate and Phosphate at the sewage samples.

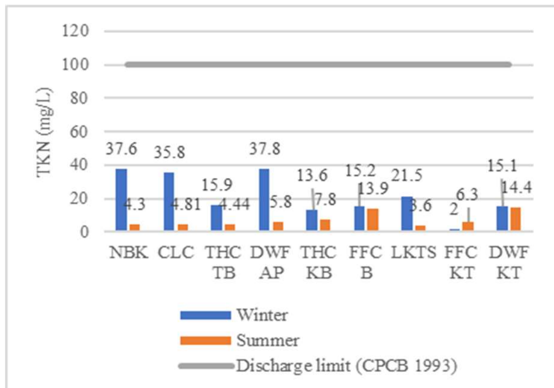

Fig. 11: TKN at the sewage samples.

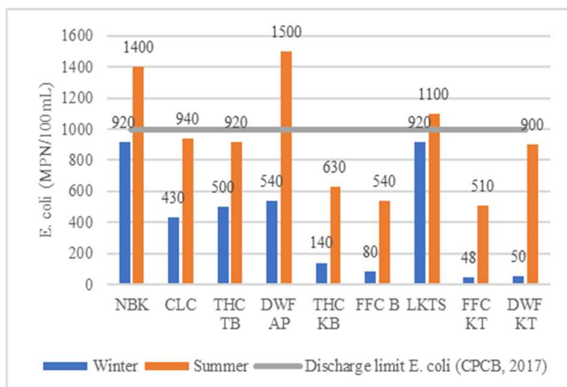

Fig. 12: E. coli at the sewage samples.

3) is the smallest (Fig. 14). To explore further and compare the mean of one group with the mean of another, a one-way analysis of variance (ANOVA) was followed. Fisher's Least Significant Difference (LSD) test was evaluated among the concentrations of inlets and outlets of the four ponds by Minitab 18 software.

The average seasonal value of each parameter of the inlets and outlets of the four selected ponds was estimated.

The pH in the outlets of the ponds was higher than the inlets but within the discharge limit (Fig. 15). The average increase in pH is 7.2 percent in the ponds ($F_{1,22}$=12.98;

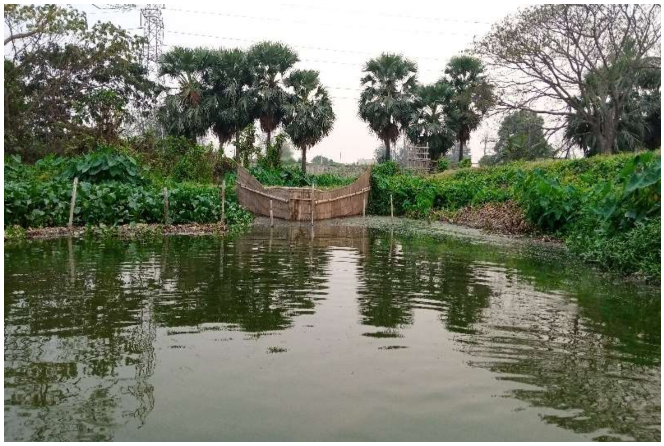

Fig. 13: A pond of EKW area.

Table 3: Location and details of the four selected ponds.

Name of the pond	Referred as	Location	Receive sewage from	Area of the pond (Hectare)
Harhare Bheri	Pond 1	22.531823; 88.446096	THC via Ghosher *Khal*;	2.9551
Sujit Mondal's Bheri	Pond 2	22.530119; 88.443782	THC via Ghosher *Khal*; diluted	1.1298
Bantala 2 No. Bheri	Pond 3	22.525048; 88.442679	DWF via Lalkuthi siphon; raw	0.4037
Dakshin Gorumara Bheri	Pond 4	22.524334; 88.445838	DWF via Lalkuthi siphon; raw	5.3804

Fig. 14: Location of four selected ponds in EKW area.

p=0.002). At moderate alkalinity, the removal of carbon dioxide by algae by the process of photosynthesis shifts the forms of alkalinity existing from bicarbonate to carbonate and from carbonate to hydroxide (Sawyer & McCarty 1978), as shown in the equation below:

$$2HCO_3^- \leftrightarrow CO_3^{2-} + H_2O + CO_2$$

$$CO_3^{2-} + H_2O \leftrightarrow 2OH^- + CO_2$$

As the pond receives an ample amount of sunlight, the algae remove CO_2 from the solution more rapidly than the CO_2 generated by the organisms present in the water. This would cause an increase in pH. However, the pH of the pond water was suitable for discharging this water into inland surface water bodies as they were within the discharge limit (CPCB 1993). This pH range is also suitable for pisciculture as the ideal pH levels for fish production are in the range of 6.5 to 9.0 (Kaoud 1999).

Alkalinity is the capacity of water to buffer pH. The buffering capacity of water should be at least 20 $mg.L^{-1}$ as $CaCO_3$ for protecting the aquatic organisms (Wurts & Durburrow1992). However, the alkalinity found in the four ponds was higher than the required buffering capacity.

The alkalinity was reduced slightly by the four ponds (Fig. 16). The average removal percent was 29.04 for alkalinity ($F_{1,22}$=13.88; p=0.001); however, CPCB does not prescribe any discharge standard regarding Alkalinity. As compared to the inlets, alkalinity was reduced as nitrification of 1 mg.L^{-1} of ammoniacal nitrogen (NH_3-N) decreased alkalinity by 7.14 mg.L^{-1} (Boyd 2016). The nutrients that are dissolved in the water are absorbed by aquatic plants. To maintain charge balance in the water, other positive ions (usually H^+) replace the ammonium ions (NH_4^+) used up by the plants. Therefore, the release of hydrogen ions lowers alkalinity. Materials such as silt, fine organic and inorganic matter, mineral dissolution (iron), phytoplankton (algae), and other microscopic organisms (bacteria, viruses, etc.) cause turbidity in water, making it murkier. These particles can be both colloidal and suspended. The turbidity is decreased in the outlets compared to the inlets. As the water is treated, the solids settle down, and turbidity should decrease a lot, but the population of algae that grow in the ponds contributes to turbidity. The turbidity was reduced in the four ponds with an average of 54% in the outlets as compared to inlets ($F_{1,22}$=41.03; p=0.0). (Fig. 17). The ponds were not very effective in reducing the chloride concentration ($F_{1,22}$=6.11; p=0.022). The average removal was noticed to be 34% in all the ponds (Fig. 18). The removal of TS was highest in the first pond, and the average removal percentage by all the ponds was 40 ($F_{1,22}$=87.88; p=0.0). The concentration of TSS in the outlets of the first, second, and fourth ponds was slightly higher than the discharge limit (Fig. 19), which was possibly contributed by algal biomass.

In all the four ponds, COD and BOD decreased significantly. The ponds worked efficiently in the removal of the COD and BOD with an average of 50.5% ($F_{1,22}$=39.55; p=0.0) and 59.1 % ($F_{1,22}$=79.98; p=0.0), respectively. The bacteria fed on the organic matter to build their biomass using the dissolved oxygen and brought down the BOD level. The average concentration of COD at the outlets of all the ponds was 66.76 mg.L^{-1}, which is far lower than the discharge limit (250 mg.L^{-1}) of CPCB 1993. The average concentration of BOD at the outlets of all the ponds was 23.3, which is also within the discharge limit of 30 mg.L^{-1} (CPCB 1993; for inland surface water); however, compared with the discharge limit for STP (20 mg.L^{-1}; CPCB 2017), the concentration is marginally higher (Fig. 20). These ponds are far from the river Kulti Gong, the final discharge point for Kolkata sewage. Downstream of the ponds, other ponds will take up this water at their intake, and it will be further treated in those oxidation ponds as EKW consists of a series of ponds. All four ponds reduced TOC ($F_{1,22}$=10.68; p=0.004) at an average rate of 36.64%, and the highest removal rate was noticed at the first pond (Fig. 21). The concentration of dissolved phosphate was 4.09, 5.89, 5.23, and 5.45 mg.L^{-1} in the inlets of four ponds, respectively (Fig. 22) indicating that the ponds are ideal for eutrophication as the threshold value of phosphorus is greater than 0.1 mg.L^{-1} for a pond to be hypereutrophic (Nemery 2019). However, the ponds were not covered with an algal bloom, indicating that the growth of phytoplankton was restricted due to the fishes grazing on them. Thus, the problem of eutrophication is mitigated. Ammonium is produced when the nitrogenous organic wastes decompose. It is a by-product of protein breakdown. All four ponds were very efficient in removing ammonium ($F_{1,22}$=41.04; p=0.00). The third and fourth ponds reduced ammonium by over 90%. The average removal rate of ammonium in the four ponds was 80.38% (Fig. 23), and phosphate removal was by over 90% ($F_{1,22}$=208.42; p=0.00) at the first, second, and third ponds. The reduction in these nutrients indicated that the aquatic plants took up the nutrients for their growth. Some amount of phosphate also got adsorbed on the surface of soil minerals, porous oxides of Fe and Al (Nichols 1983). The concentration of phosphate and ammonium was within the discharge standards of CPCB (1993). As per Sinton et al. (2007), oxidation ponds are capable of reducing *E. coli,* and the removal of *E. coli* depends on pH, DO, and sunlight (Maiga et al. 2009). The ponds of EKW worked wonderfully in reducing the indicator organism *E. coli* ($F_{1,22}$=350.17; p=0.00) with an average of 97.76% (Fig. 24), and the effluent fecal coliform content was far below the prescribed discharge limit of CPCB (2017). In the beginning, untreated sewage contains a significant amount of organic matter, which can act as a source of nutrients for various microorganisms, resulting in a high level of functional diversity. However, as the purification process continues, the organic matter in the wastewater decreases, leading to a reduction in nutrient availability for microbial growth and subsequently causing a decrease in functional diversity (Sarkar et al. 2017). The oxidation pond system efficiently serves to remove fecal coliform from the sewage (Tiley et al. 2014, Von Sperling 2007, Pescod 1992, Arthur 1983), and in the case of the four ponds studied in the EKW, the total coliform levels decreased by 99.28% on an average (Fig. 25). Sarkar et al. 2016 studied the potential of microbes to purify the sewage. They have also found that the maximum number of microbes decreases as the sewage purifies.

IMPORTANCE OF EKW

Kolkata, being an 'ecologically subsidized city' (Ghosh 2004), is blessed with unique geography: one river (Hooghly, the final stretch of the river Ganga) for drinking water abstraction on the west and another (Kulti river) for treated sewage disposal and a wetland system between the city and Kuti rivers that treats the municipal sewage by a natural

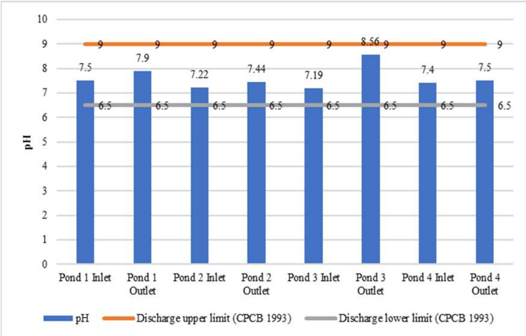

Fig. 15: pH in the inlets and outlets of ponds.

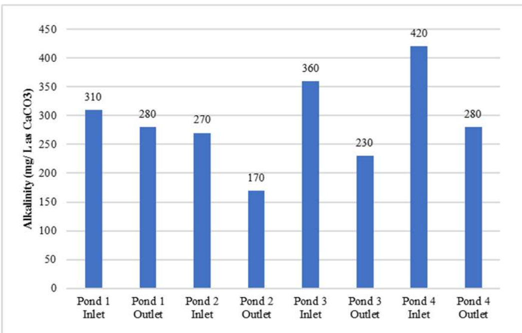

Fig. 16: Alkalinity in the inlets and outlets of ponds.

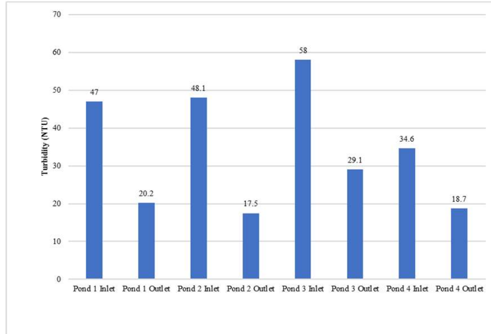

Fig. 17: Turbidity in the inlets and outlets of ponds.

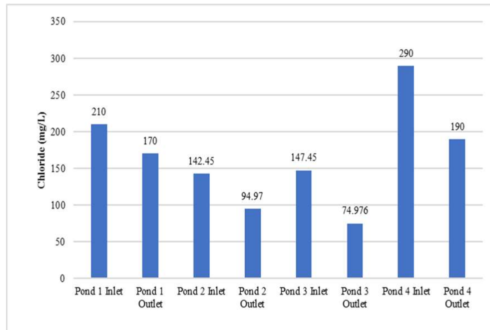

Fig. 18: Chloride in the inlets and outlets of Ponds.

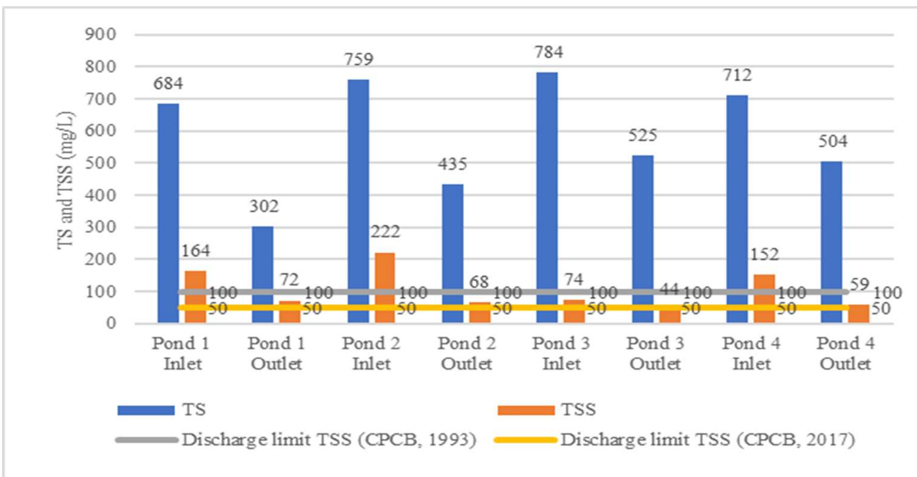

Fig. 19: TS and TDS in the inlets and outlets of ponds.

biological treatment method. The EKW stands as a unique testament to the successful integration of environmental protection and development management. The delicate balance achieved in this ecosystem, where local farmers have mastered resource recovery activities, is exemplified by the intricate interplay of aquaculture, horticulture, and agriculture (Bhattacharya et al. 2012).

At the heart of EKW's importance is its ingenious use of sewage for aquaculture and agriculture. This practice not only showcases environmental innovation but also yields substantial benefits. The sewage-fed fisheries in EKW contribute significantly to the region's annual fish production. The treated water discharged from these fish ponds is channeled into irrigating paddy fields and

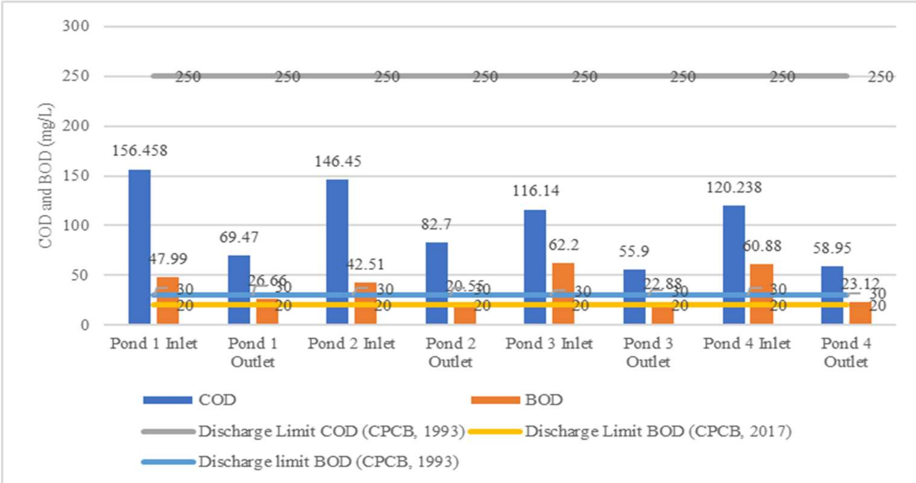

Fig. 20: COD and BOD in the inlets and outlets of ponds.

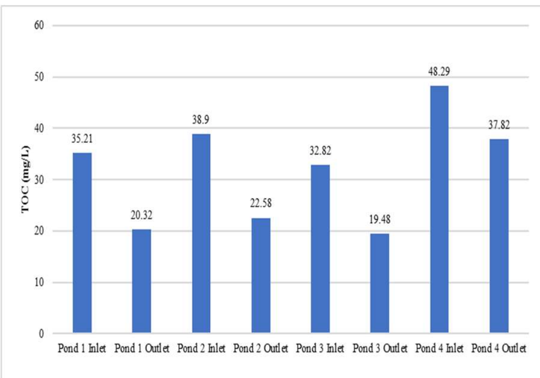

Fig. 21: TOC in the inlets and outlets of ponds.

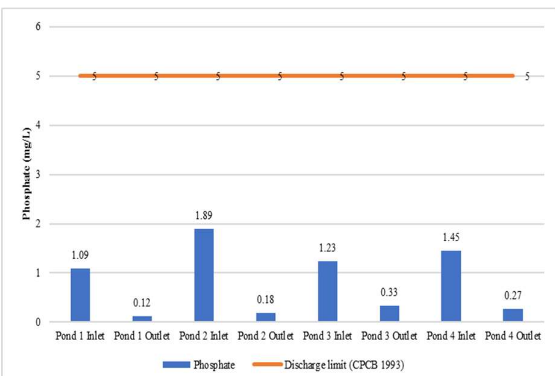

Fig. 22: Phosphate in the inlets and outlets of ponds.

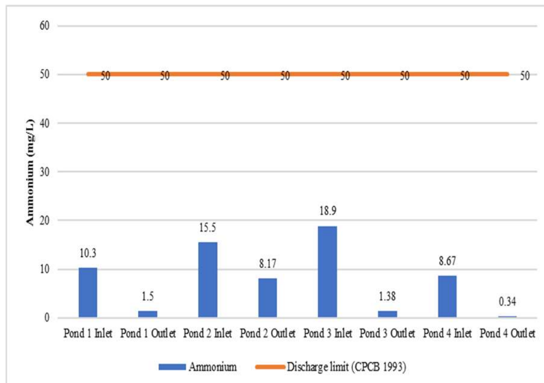

Fig. 23: Ammonium in the inlets and outlets of ponds.

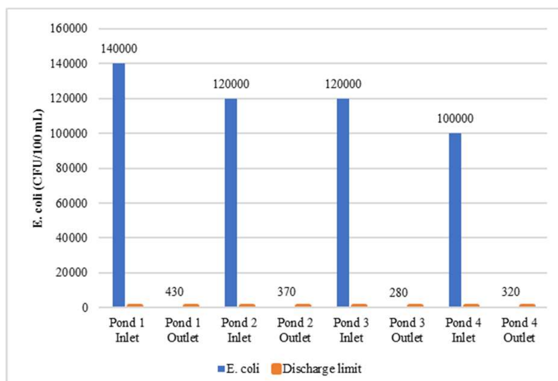

Fig. 24: *E. coli* in the inlets and outlets of ponds.

agriculture farms, creating a closed-loop system of resource utilization.

The organic wastewater discharged by the city of Kolkata finds a purpose in EKW as they are utilized as valuable manure for cultivating fresh vegetables. This not only serves as an effective waste management strategy but also economically benefits the local farmers. By repurposing organic waste, the system minimizes the need for external

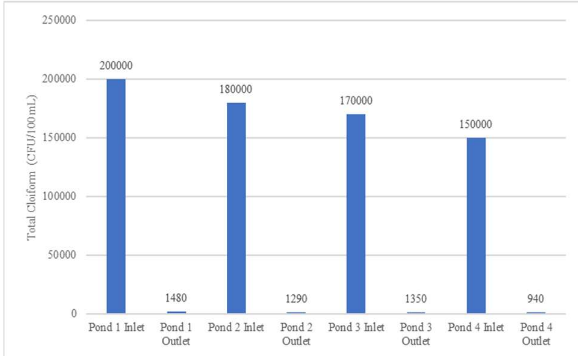

Fig. 25: Total coliform in the inlets and outlets of ponds.

fertilizers, thus reducing costs and increasing overall profitability.

Resource recovery systems from the EKW are a revenue earner. EKW produces about 11,000 metric tonnes of fish per year (Government of West Bengal 1997). Regularly, the garbage farms generate an average of 152.41 metric tons of freshly harvested vegetables and an annual output of 16,000 tonnes of paddy (EKWMAP 2021). Mukherjee (2018) calculated the cost of sewage treatment per million liters for STPs as 1246 INR. The sewage cleaning cost by EKW was calculated by subtracting the cost of fish production from the profit earned by selling the fish. The cost of fish production was calculated by summing the rent paid by the fishermen for using the ponds. It is about -10302.00 INR per million liters (the value is negative as the profit from selling fish was higher than the cost of production).

Being next to the city, EKW faces constant threats from rapid urbanization, leading to a 26% shrinkage in wetlands from 1973 to 2010 (Parihar et al. 2013) and 57% land acquisition from 1991 to 2018 (Mandal et al. 2019). The treatment system also depends on the continuous supply of sewage from the city. So, it is of utmost importance to protect the EKW area from land use change and maintain an unremitting supply of sewage on a daily basis.

CONCLUSION

The current study on East Kolkata Wetlands revealed a complex sewage drainage system delivering an average of 909.07 MLD in winter and 709.34 MLD in summer. EKW efficiently treats the sewage, demonstrating 59.1% BOD removal and a 99.28% reduction in fecal coliform. The natural treatment system excels in removing ammoniacal nitrogen (80.38%) and phosphate (90%). Local management practices showcase waste-to-wealth recycling, offering a self-sustaining model that can be replicated as a low-cost sanitation option for smaller cities with ample sunshine. The Ramsar Convention recognizes EKW as one of the 17 tutorial wetland ecosystems in the world and the only such from India. The symbiotic relationship between environmental protection and economic prosperity in EKW serves as a model for sustainable development, emphasizing the need for preservation amid looming threats.

ACKNOWLEDGMENT

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