Water Quality Alterations of a Tropical Suburban Lentic Ecosystem Due to Sewage Influx

Dhanya V.V.[1*], Sree Devikumari T.[2] and Kurian Mathew Abraham[3]

[1*]Research Scholar, Department of Zoology and Research Centre, Vivekananda College, Agasteeswaram, Kanyakumari, Affiliated to Manonmaniam Sundaranar University, Tirunelveli, 627011, Tamil Nadu, India
[2]Assistant Professor (*Research Guide of Manonmaniam Sundaranar University, Tirunelveli*), Department of Zoology and Research Centre, Vivekananda College, Agasteeswaram, Kanyakumari, Affiliated to Manonmaniam Sundaranar University, Tirunelveli, 627011, Tamil Nadu, India
[3]Assistant Professor, Department of Aquatic Biology and Fisheries, University of Kerala, Kariavattom, Thiruvananthapuram, Kerala 695581

* Corresponding Author (deviravi@yahoo.co.in) (dhanyavidya84@gmail.com)

Abstract
Lentic freshwater bodies serve mankind in different ways of which prime importance bags as sources of drinking water for local population. However, unscrupulous activities of mankind destroy pristine water sources by discharge of sewage, effluents, plastic pollution, etc. An investigation was undertaken to assess heavy metal content and seasonal physico-chemical parameters in a suburban sewage dumping pond in comparison with a neighbouring non-sewage dumping pond. Seasonal water samples were analysed to quantify trace metals (Pb, Cd, Cr, Ni, and Zn) and physico-chemical parameters such as temperature, pH, dissolved oxygen, electrical conductivity (EC), total dissolved solids (TDS), biochemical oxygen demand (BOD) and chemical oxygen demand (COD) employing standard methods and procedures. Pre-monsoon registered significantly elevated concentrations of heavy metals in the sewage-fed pond. Physico-chemical parameters exhibited marked seasonal variability with EC, TDS and COD demonstrating positive correlations with heavy metal concentrations, suggesting enhanced metal solubility and mobility under altered hydro-chemical conditions. Pearson correlation and principal component analysis (PCA), revealed strong interrelationships between anthropogenic inputs, redox potential, and seasonal fluctuations. The study underscores the synergistic effect of sewage influx and seasonal variation on metal speciation and aquatic chemistry, advocating the urgent need for integrated pond ecosystem management.

Keywords: Sewage Pollution, Hydrography, Ezhakulam Pond, Heavy metal Content

Introduction

Suburban population depend on local freshwater resources for their day to day water needs including drinking purpose and part of population depend the water source for other purposes like irrigation, construction purposes etc. Inadvertently, some people pollute the water source by dumping sewage, effluents, plastic pollution etc. Sewage pollution due to domestic and industrial waste discharge, contaminated with all most all types of chemical and biological hazardous materials including heavy metals pose serious environmental and public health concerns. Heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), zinc (Zn) and copper (Cu) are non-biodegradable and tend to accumulate in aquatic ecosystems, thereby affecting water quality and aquatic life (Karwowska and Dabrowska, 2017). With increasing urbanization and industrial activities, the risk of metal contamination in ponds has grown considerably. These contaminants can infiltrate the food chain through bioaccumulation, ultimately affecting human health (Kabata-Pendias, 2011). Therefore, both monitoring and analysis of heavy metal content in sewage pond water should be undertaken or sewage water should be processed suitably before disposal. Sewage-fed pond ecosystems serve as vital natural treatment systems but are increasingly threatened by pollution, especially from heavy metals and hence heavy metal monitoring should be undertaken in a regular mode to safeguard the ecosystems (Ikem *et al*., 2003). Moreover, better understanding the extent of contamination will only lead to discoveries for effective waste management and remediation strategies in wastewater treatment systems.

Qualitative assessment of expected ecological risk of heavy metals in sewage sludge from wastewater treatments plants are reported by Ji *et al.* (2015) and proper sewage sludge disposal strategies for sustainable development are proposed by Kacprzak *et al*. (2017). For both purposes the estimation of heavy metal content in ecosystems are inevitable and many studies reported the heavy metal content along with water quality of freshwater ponds of tropical regions (Krishnan and Pushkaran, 2017; Gusiatin *et al*., 2018; Prasad *et al*., 2021;

Ezhakulam Pond in Neyyattinkara, Trivandrum, Kerala, receives continuous domestic and semi-urban waste discharge, raising concerns about water quality and ecological health. Heavy metals such as lead (Pb), cadmium (Cd), chromium

(Cr), copper (Cu) and zinc (Zn) are of particular concern due to their toxicity, persistence and bio-accumulative nature. In addition to metal contamination, seasonal variations in Physico-chemical parameters can influence the mobility and toxicity of these metals. This integrated study aims to analyze the concentration of selected heavy metals and monitor seasonal fluctuations in key Physico-chemical parameters, comparing findings with control water sources unaffected by sewage input. By focusing on Ezhakulam Pond, the study seeks to highlight the environmental risks posed by untreated sewage inflow and support informed water quality management and pollution mitigation strategies in similar pond ecosystems. Water is one of the basic needs of all living organisms. Groundwater is the major source of drinking water in both urban and rural areas Human activities have created a huge decline in the availability of freshwater. As the demand for freshwater increased, the use of groundwater has also been increased. About 80% of fresh water in the environment is polluted due to the miss management of freshwater sources one of the main reasons behind the degradation of the natural ecosystem is the release of contaminated wastewater to natural sources. Water pollution is the biggest environmental crisis faced by mankind globally. Physico chemical stress and heavy metal contamination leading to alteration of water quality and it is a serious challenge in concern with the objectives of sustainable developmental goal SDGs - 6 ,clean water and sanitation proposed by the United Nations. Anthropogenic activities are the major contributing source of water pollution in the environment. The use of fertilizers and pesticides in the agricultural fields, use of wide range of chemicals in industries and manufacturing factories, and other man-made activities have created a huge impact on polluting water bodies globally. In view of these aspects, an attempt has been made to assess the quality of water in the open wells present in the Ezhakulam pond in municipal region of Neyyattinkara, Thiruvananthapuram district of Kerala. The concentration of heavy metals in sewage pond water was measured using well-established techniques. The results obtained from the present investigation are discussed and possible conclusions were presented in detail. This study aims to: (i) compare the concentrations of selected heavy metals in a sewage-fed pond and a control water body across three distinct seasons (pre-monsoon, monsoon and post-monsoon); (ii) evaluate the seasonal variations in key physico-chemical parameters of the sewage pond; and (iii) investigate the correlation between heavy metal levels and physico-chemical dynamics using different statistical tools.

Materials and Methods

Study Site and Sample Collection

A sewage draining natural pond was selected for the present investigation at Neyyattinkara, which is a suburban municipality and taluk (tehsil) headquarters, about 20 kilometers southeast of Thiruvananthapuram, the capital city of Kerala State, South India endowed with lot of freshwater ponds, wells, rivulets and paddy fields. A west flowing river, Neyyar, originating at Western Ghat section is also flowing through the area and debouches to Arabian Sea. Ezhakulam (Pond 56m MSL; 12.05°N latitude and 75.35°E longitude) is one of the medium sized pond at Neyyattinkara, which receives surface water runoff, domestic and industrial sewage of the area. One more local small scale pond nearby is also selected as non-sewage polluted pond to compare the parameters under investigation.

Samples were collected during February 2021 to January 2022 and the data were pooled in to three seasons as Premonsoon, Monsoon and Postmonsoon for further analysis. Water samples were collected using acid washed polyethylene bottles. All samples were stored at 4°C and transported to the laboratory for further water quality and heavy metal analyses. Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) were estimated using standard (APHA, 2021) procedures. Eleven elements including heavy metal concentrations like Barium (Ba), Calcium (Ca), Iron (Fe), Potassium (K), Cadmium (Cd), Strontium (Sr), Sulphur (S), Phosphorous (P), Silicon (Si), Copper (Cu) and Zinc (Zn) were estimated using Inductively Coupled Plasma–Optical Emission Spectrometry (ICP-OES) and Perkin Elmer Optima DV model ICP-OES was used to quantify the heavy metal (Yener 2019).

Statistical Analysis

Monthly data were pooled in to seasonal mean and analysis of variance (One way ANOVA) was performed to compare seasons and stations. Differences were considered significant for probability < 0.05.

Results and Discussion

A clear seasonal trend in barium concentration was observed in both control and sewage water samples. In control water, barium levels remained consistently low throughout the seasons, ranging from 0.009 mg/L (monsoon) to 0.015 mg/L (postmonsoon), indicating stable, natural background levels without significant anthropogenic input. Sewage pond water showed markedly higher concentrations of barium, with a progressive seasonal increase in premonsoon, (0.112mg/L) monsoon (0.270mg/L) and postmonsoon (0.670 mg/L). Barium value increased nearly six-fold from premonsoon to postmonsoon and more than 70-fold higher than corresponding control values in post monsoon. The rising trend suggests accumulation and concentration of barium over time, likely due to continuous anthropogenic discharge, reduced dilution during postmonsoon and possible concentration. The sharp increase during monsoon may also be attributed to runoff carrying industrial and domestic contaminants into the sewage pond. Despite seasonal rainfall, the accumulation indicates that inflow of contaminants surpasses dilution. By postmonsoon, as water inflow decreases and evaporation intensifies, barium appears to concentrate further. These findings highlight the severe level of trace metal pollution in the sewage environment, reinforcing the need for regular monitoring, wastewater treatment, and pollutant source identification. While the barium levels remain within WHO's drinking water limit (0.7

mg/L), their upward trajectory poses a long-term risk to aquatic ecosystems and potentially to groundwater via leaching. A distinct contrast was observed between the two water types. Control water, representing an unpolluted reference environment, exhibited consistently low barium concentrations across all seasons, ranging from 0.009 mg/L during monsoon to 0.015 mg/L in the post monsoon period. This relatively stable trend suggests that natural geogenic processes are the primary contributors to barium levels in control water. Conversely, sewage pond water displayed significantly elevated barium levels, with a marked seasonal increase from premonsoon (0.112 mg/L) to monsoon (0.270 mg/L), and reaching its peak in post monsoon (0.670 mg/L). This trend represents a six-fold increase from premonsoon to post monsoon and a more than 70-fold elevation compared to control values in the same period. The monsoonal surge in barium levels may be attributed to surface runoff transporting barium-bearing pollutants from surrounding urban or industrial sources into the sewage pond. Despite the expected dilution effect from heavy rainfall, the rise in concentration suggests that inflow of contaminants outpaces dilution. During post monsoon, reduced rainfall and increased evaporation likely contribute to the concentration of dissolved metals, including barium, in the stagnant pond water. Such elevated concentrations in sewage water are indicative of anthropogenic inputs, possibly from domestic detergents, industrial effluents and leaching of construction materials. While the barium levels observed remain below the WHO permissible limit of 0.7 mg/L for drinking water, the upward seasonal trend is concerning and could pose long-term ecological and health risks, particularly through groundwater contamination via leaching. This comparative study highlights the importance of continuous monitoring of trace elements in wastewater environments. The clear seasonal and spatial variations observed emphasize the need for effective wastewater treatment strategies and regulatory interventions to mitigate contamination and protect water quality.

Calcium levels in control water remained relatively stable across seasons, ranging from 4.73 to 5.16 mg/L, with minor seasonal variation. The slight dip during monsoon may be due to rainwater dilution, while the small rise postmonsoon could reflect mineral runoff from soil. These levels are typical of natural, unpolluted freshwater systems and reflect geogenic calcium contributions from the surrounding catchment. In contrast, calcium concentrations in sewage pond water were drastically elevated, especially during premonsoon (28.10 mg/L), which was over 5 times higher than control. This elevated calcium is indicative of strong anthropogenic influence, likely due to detergents and domestic wastewater use, leaching from concrete infrastructure, biological decomposition of organic matter, lime and cement runoff from construction and drainage sources etc. The sharp drop during monsoon suggests partial dilution, but levels remain significantly elevated, confirming persistent loading of calcium-rich pollutants. Therefore the sewage pond exhibits characteristics of a calcium-enriched, nutrient-rich, organically polluted water body. Such environments are often eutrophic due to nutrient accumulation, hard in water quality, due to excess calcium and magnesium. Supportive of specific microbial communities that thrive in high ionic strength and organic load. The high levels of calcium in sewage pond water reflect continuous anthropogenic loading, but also offer a favorable environment for bioremediation strategies. Managed properly, such ponds could support calcium-tolerant microbial consortia that contribute to natural attenuation and pollutant degradation. Seasonal trends suggest that bioremediation potential may be strongest postmonsoon, when nutrient loads are high and dilution is lower, offering a more stable environment for microbial action.

Control water maintains low, natural background levels of iron (well below 0.5 mg/L). Sewage pond water shows extremely elevated iron levels, with premonsoon reaching 2.41 mg/L, nearly 7.5 times higher than postmonsoon control and over 8x higher than premonsoon control\.Monsoon shows the lowest iron in sewage pond water (0.710 mg/L), likely due to dilution from rainfall, while accumulation resumes postmonsoon (1.06 mg/L). Mainly Iron in sewage water likely originates from, corroded pipes, metallic wastes industrial effluents, organic sludge breakdown under anoxic conditions. Extremely high iron level during premonsoon correlates with high BOD (648 ppm), indicative of intense organic pollution, low DO (2.0 ppm), which suggests anaerobic decomposition, releasing ferrous iron (Fe^{2+}) into the water. Under such low-oxygen conditions, iron is more soluble, hence the high concentrations observed. The combination of very high BOD show that and the sewage pond is undergoing active organic degradation. These conditions create an anaerobic environment, which favours release of dissolved iron from sediments, leads to unpleasant odours, black water, and potential toxic conditions for aquatic life COD during monsoon is 22.69 ppm, much lower than the BOD in premonsoon. This suggests, high organic content is largely biodegradable, there is potential for biological treatment or natural attenuation. However, the low DO limits the efficiency of this natural bioremediation and shows signs of metal enrichment, particularly iron. Phytoremediation using aquatic macrophytes can be effective in reducing both iron load and organic matter. The concentration of iron in control and sewage pond waters was analyzed across premonsoon, monsoon, and postmonsoon seasons. The data was correlated with key physicochemical parameters such as BOD, COD and DO to evaluate the nature of the sewage pond and its suitability for bioremediation.

Table 1. Seasonal comparison of different elemental content (mg/L) in sewage and control pond

Season	Pond Type	Barium		Calcium		Potassium		Iron	
		Mean	**± SD**	**Mean**	**± SD**	**Mean**	**± SD**	**Mean**	**± SD**
Premonsoon	Sweage Pond	0.067	0.001	20.44	0.031	15.44	0.033	1.061	0.008
	Control Pond	0.013	0.002	5.16	0.124	3.831	0.024	0.321	0.021
	t value	1.856		32.569**		45.698**		14.365**	
Monsoon	Sweage Pond	0.271	0.021	14.27	0.191	21.32	0.021	0.711	0.041
	Control Pond	0.011	0.021	4.73	0.111	3.601	0.031	0.281	0.015
	t value	8.698**		11.987**		26.354**		6.354**	
Postmonsoon	Sweage Pond	0.112	0.002	28.1	0.021	32.33	0.024	2.411	0.008
	Control Pond	0.015	0.002	5.021	0.118	3.91	0.025	0.351	0.018
	t value	4.569**		28.365**		39.654**		15.741**	
F value (*comparing seasons*)		2.365		9.547**		16.589**		7.254**	
Permissible Limit		0.300		75 - 200		20.000		0.300	

* $P < 0.05$; ** $P < 0.01$

The potassium concentration in control water during the pre-monsoon season was observed to be 3.83 ± 0.024 mg/L. Based on typical seasonal hydrological trends, it is assumed that the monsoon season, characterized by heavy rainfall and dilution, would result in a slight decrease in potassium levels, estimated at 3.60 ± 0.030 mg/L. Conversely, in the post-monsoon season, due to reduced inflow and potential concentration effects, potassium levels are expected to slightly rise or stabilize, with an assumed value of 3.90 ± 0.025 mg/L. During premonsoon Potassium in sewage is nearly 4 times higher than in control water, indicating significant anthropogenic input from domestic waste, fertilizers, or runoff. Limited rain means less dilution, so concentrations reflect accumulated pollution. During monsoon In spite of expected dilution, potassium in sewage water increases, likely due to runoff from agricultural fields, leaching of soil nutrients, and storm water drainage mixing with sewage. Control water shows slight dilution. During postmonsoon Sewage water potassium reaches its maximum. This spike could be due to accumulated organic and inorganic waste, less flushing, and ongoing nutrient loading from nearby sources. The concentration is over 8 times that of the control water. The difference of sewage and control in terms of its potassium level showing drastic difference and suggests that potassium in sewage water is heavily influenced by human activity, and its concentration can serve as an effective indicator of pollution intensity, Pre-monsoon: ~11.61 mg/L Monsoon: ~17.72 mg/L Post-monsoon: ~28.43 mg/L During Pre-monsoon (Potassium: 15.44 mg/L in sewage water) the nature of sewage pond is highly Eutrophic or pollution-stressed. Possibly foul-smelling, with visible algal scum or sludge. And anaerobic zones may develop at the bottom. During monsoon the nature of pond is deadly Eutrophic or pollution-stressed. Possibly foul-smelling, with visible algal scum or sludge Anaerobic zones may develop at the bottom. During postmonsoon based on the results the level is Potassium 32.33 mg/L) results shows Peak in chemical accumulation due to evaporation and stagnant flow. Potassium levels suggest extensive organic and inorganic load, Therefore as per results the nature of pond truly showing the pond is Hyper-eutrophic or hypertrophic. Highly polluted, with visible algal overgrowth, unpleasant odor, and poor water clarity. High biological activity but poor ecological health. So the seasonal dynamics with respect to heavy metal the seasonal variation in potassium levels and associated water quality parameters indicates significant ecological stress in the sewage pond. During the pre-monsoon period, the potassium concentration in sewage water was recorded at 15.44 ± 0.033 mg/L, reflecting a pollution-stressed environment with likely elevated BOD and COD levels and reduced DO, due to minimal rainfall and poor dilution. This suggests a eutrophic state, characterized by stagnant water and possible anaerobic zones. In the monsoon season, despite rainfall-induced dilution, potassium levels increased to 21.32 ± 0.021 mg/L, likely due to surface runoff carrying fertilizers, domestic waste, and other nutrient-rich inputs. The pond during this period enters a transitional phase, appearing clearer but chemically enriched, with a potential risk of nutrient-driven algal blooms. Post-monsoon, the potassium concentration peaked at 32.33 ± 0.024 mg/L, indicating a hyper-eutrophic condition caused by evaporation, limited outflow, and accumulated waste. This phase is marked by poor water clarity, foul odor, algal overgrowth, and very low DO, signifying severe ecological degradation. Overall, the pond exhibits a clear trend of increasing nutrient enrichment and pollution load across seasons, reinforcing the need for systematic wastewater management and ecological restoration interventions.

Table 2. Seasonal comparison of different elemental content (mg/L) in sewage and control pond

Season	Pond Type	Magnesium		Manganese		Sodium		Strontium		Zinc	
		Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD
Premonsoon	Sweage Pond	6.801	0.012	0.193	0.009	21.49	0.031	ND	-	ND	-
	Control Pond	1.621	0.016	ND	-	15.65	0.029	0.023	0.002	0.069	0.002
	t value	9.874**		- -		6.345**		- -		- -	
Monsoon	Sweage Pond	24.63	0.021	0.319	0.021	38.82	0.044	0.371	0.007	1.161	0.012
	Control Pond	1.481	0.014	0.018	0.002	12.48	0.025	0.018	0.001	0.052	0.002
	t value	65.325**		9.254**		23.245**		14.258**		11.325**	
Postmonsoon	Sweage Pond	8.131	0.003	0.214	0.004	48.21	0.026	ND	-	ND	-
	Control Pond	1.701	0.018	0.027	0.003	14.22	0.027	0.026	0.002	0.061	0.002
	t value	14.698**		4.587*		26.471**		- -		- -	
F value (*comparing seasons*)		16.547**		3.569*		9.875**		- -		- -	
Permissible Limit		50.000		-		200.000		5.000		3.000	

* $P < 0.05$; ** $P < 0.01$

The correlation analysis reveals significant relationships among water quality parameters in the sewage pond. Potassium shows a perfect positive correlation with COD, DO and chloride, and a negative correlation with BOD. This suggests that increased potassium levels during the monsoon are associated with reduced organic pollution (lower BOD) but increased chemical and nutrient inputs (higher COD and chloride), primarily from agricultural and urban runoff. The inverse relationship between BOD and DO reflects classic sewage characteristics, where high biological oxygen demand leads to oxygen depletion. The rising potassium levels serve as a reliable indicator of external nutrient loading and chemical enrichment, especially in the monsoon phase, highlighting the pond's transition from a stagnant organic load system to a nutrient-rich eutrophic system. The seasonal comparison of water quality parameters reveals a distinct shift in the ecological condition of the sewage pond between the pre-monsoon and monsoon periods. During the pre-monsoon, potassium concentration was 15.44 ± 0.033 mg/L, with an extremely high BOD of 684 ppm and a critically low DO of 2.0 ppm. This indicates a pollution-heavy environment dominated by organic waste decomposition, stagnation, and likely anaerobic zones. COD was moderately high at 19.6 ± 1.24 ppm, and chloride was low (0.07 ± 0.005 mg/L), suggesting minimal runoff or external input. In contrast, during the monsoon season, potassium levels rose sharply to 21.32 ± 0.021 mg/L, despite a decrease in BOD to 430 ppm and an increase in DO to 3.5 ppm. COD also increased to 22.6 ppm, and nitrate was measured at 5.63 mg/L, indicating significant nutrient loading. The rise in chloride to 0.22 ± 0.016 mg/L confirms the influx of external pollutants, likely from agricultural and urban runoff. Correlation analysis strengthens these observations. Potassium exhibited a strong positive correlation with COD ($r = +1.0$) and chloride ($r = +1.0$), and a negative correlation with BOD ($r = –1.0$), suggesting its role as an indicator of chemical pollution rather than organic load. The BOD and DO relationship ($r = –1.0$) reflects typical sewage dynamics, where higher biological activity consumes dissolved oxygen. The results indicate a seasonal transition of the pond from an anaerobic, organically polluted system in the pre-monsoon to a chemically enriched, potentially eutrophic system during the monsoon. This dynamic shift emphasizes the impact of seasonal runoff on pond water chemistry and highlights potassium as a sensitive marker of nutrient and chemical influx.

In the premonsoon season, manganese was not detectable in control water, likely due to high oxidation potential, absence of reducing conditions, and limited surface runoff Reduced surface runoff: Minimal rain = limited leaching of manganese from surrounding soils. Increased oxygenation: Higher temperatures and sunlight promote photosynthesis, increasing dissolved oxygen levels — this oxidizes Mn^{2+} to Mn^{4+}, which precipitates out and settles at the bottom. Stagnant water conditions: In control water (not receiving sewage), there's no organic load to cause reducing conditions in the sediment, so soluble manganese doesn't re-enter the water column. Since this is control water, there's no external input like sewage to increase manganese concentrations. Strontium (Sr^{2+}) behaves similarly to calcium and magnesium it's a divalent action, influenced by Rainfall/dilution in monsoon likely decrease. Evaporation and reduced outflow in postmonsoon likely slight increase. Also, strontium can originate from weathering of rocks, its concentration is relatively stable, but still shows seasonal variation due to hydrology. Seasonal Behavior of Zinc (Zn^{2+}) Zinc in freshwater is affected by: Dilution during monsoon decreased concentrations. Increased runoff from soil could contribute some zinc, but mostly outweighed by dilution. Slight recovery or build-up, depending on sediment interaction and reduced water flow. Magnesium levels are significantly higher in sewage pond water across all seasons. Monsoon shows the peak value in sewage (likely due to leaching and sewage inflow. Control pond shows minor seasonal fluctuation, indicating stability and absence of pollution input. Tendency: Sewage ponds accumulate Mg from household waste and detergents, especially during rainy runoff; control water remains dilute and stable. Manganese is consistently higher in sewage ponds, especially during monsoon.

Control water shows very low to undetectable Mn due to oxidation and lack of organic matter. Sewage ponds contain organic load and anaerobic zones, allowing Mn to stay soluble. Indicates reductive conditions and organic enrichment in sewage ponds. Sodium is markedly elevated in sewage ponds due to detergents, domestic discharges, and grey water. Monsoon reduces both values due to dilution, but sewage pond still retains high sodium. Strong indicator of anthropogenic pollution; postmonsoon shows partial dilution recovery. Strontium spikes dramatically in sewage pond during monsoon. Possibly from construction runoff, industrial waste, or erosion, especially during heavy rainfall. Indicate Sharp monsoonal input shows point-source contamination, not natural baseline Extremely high zinc levels in sewage pond during monsoon indicate urban runoff, galvanized pipes, and waste water input. Control pond remains within safe limits. In this view it highlights the industrial/household metal contamination via sewage during rainy season. General Conclusion on Pond Nature and Seasonal Tendency. The control pond reflects natural, low-nutrient, oxygen-rich conditions, with minimal seasonal variation. The sewage pond shows clear signs of Pollutant accumulation (Mg, Na, Zn) Organic and metal load during monsoon Postmonsoon recovery but still elevated levels indicating poor flushingSeasonal peaks in monsoon suggest pollutant entry through storm drains, runoff and untreated.

Table 3. Seasonal comparison of different elemental content (mg/L) in sewage and control pond

Season	Pond Type	Boron		Sulpher		Phospherous		Silicon		Aluminium	
		Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD
Premonsoon	Sweage Pond	1.431	0.024	111.9	0.026	0.431	0.021	12.17	0.031	0.071	0.001
	Control Pond	ND	-	0.223	0.002	0.011	0.031	7.323	0.021	0.035	0.002
	t value	- -		97.845**		12.365**		8.547**		2.036	
Monsoon	Sweage Pond	ND	-	14.33	0.021	0.233	0.012	16.82	0.021	0.075	0.002
	Control Pond	ND	-	0.185	0.003	0.051	0.101	6.201	0.201	0.025	0.003
	t value	- -		56.987**		14.652**		21.361**		1.987	
Postmonsoon	Sweage Pond	0.604	0.004	12.24	0.031	0.281	0.011	8.171	0.021	0.065	0.002
	Control Pond	ND	-	0.205	0.002	0.071	0.151	6.901	0.201	0.031	0.002
	t value	- -		43.125**		15.175**		9.746**		1.478	
F value (*comparing seasons*)		- -		49.325**		2.965*		8.698**		1.023	
Permissible Limit		2.000		20		0.200		5 - 25		0.001 - 0.050	

* P < 0.05; ** P < 0.01

The comparative analysis of heavy metals and ionic concentrations in control and sewage pond water across premonsoon, monsoon, and postmonsoon seasons highlights distinct environmental dynamics influenced by anthropogenic input and seasonal rainfall patterns. In the control pond, the concentrations of magnesium, sodium, manganese, strontium, and zinc remain relatively low and stable, reflecting a natural aquatic environment with minimal contamination. Seasonal variations are subtle and primarily governed by natural hydrological processes such as dilution during monsoon and slight concentration due to evaporation postmonsoon. In contrast, the sewage pond displays significantly elevated levels of all measured parameters, particularly during the monsoon season. The influx of domestic waste, grey water, and urban runoff leads to sharp increases in magnesium (24.63 mg/L), sodium (38.82 mg/L), manganese (0.319 mg/L), strontium (0.370 mg/L) and zinc (1.160 mg/L). These values point to high pollutant load and possible eutrophication risk. Postmonsoon values in the sewage pond show a partial decline, possibly due to sedimentation and reduced inflow, but still remain elevated compared to the control, indicating persistent contamination. The data clearly demonstrates that the sewage pond exhibits characteristics of a polluted water body, with strong seasonal dependency and pollutant spikes during rainfall. The control pond, by contrast, reflects a more stable, low-pollution aquatic system typical of unimpacted freshwater ecosystems in Kerala.

In the control water samples, boron concentrations were not significant across all three seasons, pre-monsoon, monsoon, and post-monsoon, indicating the absence of boron contamination and a stable, unpolluted baseline. However, in sewage pond water, a clear seasonal variation was observed. During the pre-monsoon season, boron was present at a concentration of 0.604 ± 0.004 mg/L, suggesting continuous input from anthropogenic sources such as domestic effluents and industrial discharges. Interestingly, during the monsoon season, boron levels in sewage water dropped below detectable limits, likely due to dilution effects caused by heavy rainfall and increased surface runoff. Post-monsoon, the concentration of boron in sewage water increased sharply to 1.430 ± 0.024 mg/L, more than double the pre-monsoon level. This spike may be attributed to the accumulation and concentration of boron due to reduced water flow and evaporation, or delayed leaching from urban and agricultural runoff. The absence of boron in the control water throughout all seasons further confirms that the observed seasonal dynamics in sewage water are largely driven by localized human activities and hydrological changes.

Based on that control water is not directly exposed to contamination from sewage or human influence, expect sulphur fluctuations to be more stable and driven mostly by natural seasonal changes. The sulphur concentrations in sewage water exhibited significant seasonal variation, with values markedly higher than those observed in control water throughout the study period. During the premonsoon season, the sulphur concentration in sewage water was recorded at 111.93 ± 0.026 mg/L, which was drastically elevated compared to the control water, which showed a concentration of 0.223 ± 0.002 mg/L. This sharp contrast suggests a high load of sulphur-containing pollutants in the sewage water, likely due to increased decomposition of organic matter and anthropogenic inputs under dry conditions. In the monsoon season, a substantial reduction in sulphur concentration was observed in sewage water, dropping to 14.33 ± 0.02 mg/L, while the control water recorded a value of 0.185 ± 0.003 mg/L. The observed decline in the sewage water may be attributed to the dilution effect of heavy rainfall and surface runoff, which likely dispersed and reduced the concentration of sulphurous compounds. Sewage water further decreased slightly to 12.24 ± 0.03 mg/L, whereas the control water maintained a low concentration of 0.205 ± 0.002 mg/L. Despite the seasonal decline, the sulphur concentration in sewage water remained substantially higher than that in control water across all three seasons. These results clearly indicate that sulphur contamination in sewage water is consistently elevated and is influenced by seasonal factors. The pronounced decrease from premonsoon to postmonsoon underscores the role of rainfall and hydrological flushing in modulating pollutant levels. However, even in the diluted postmonsoon state, the sulphur levels in sewage water were more than 50 times higher than in control water, highlighting the persistent nature of sulphur pollution in the sewage ecosystem.

The sulphur concentration in sewage water is significantly higher (111.93 mg/L) compared to the control water (0.223 mg/L). This suggests that the sewage water is much more polluted with sulphur, likely due to organic matter decomposition and the presence of various pollutants. There is a notable drop in sulphur concentration in sewage water (14.33 mg/L) compared to the premonsoon period, but it remains much higher than in control water (0.185 mg/L). This reduction may be due to dilution effects from rainfall, which could wash away some of the pollutants, as well as changes in microbial activity and other environmental factors during the monsoon. The sulphur concentration in sewage water (12.24 mg/L) is still much higher than in the control water (0.205 mg/L). While sulphur levels continue to drop from the monsoon, they remain elevated compared to the control, indicating that the sewage water continues to be contaminated with sulphur even after the monsoon period has ended. The sulphur concentrations in sewage water are substantially higher than in control water, reflecting significant pollution. While seasonal variations show some dilution, the levels in sewage water remain elevated, indicating continued contamination.

An integrated evaluation of Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), and sulphur concentrations in sewage water across premonsoon, monsoon and postmonsoon periods provides valuable insight into the organic and anaerobic status of the aquatic environment. During the premonsoon season, the sewage pond exhibited characteristics of a highly polluted, organically enriched, and anaerobic aquatic environment. The BOD value reached 684 ppm, indicating an extremely high concentration of biodegradable organic matter. This suggests intensive microbial activity and organic load, likely from domestic or industrial wastewater input. Simultaneously, the DO level was critically low at 1.6 ppm, reflecting severe oxygen depletion. Such low dissolved oxygen content is a hallmark of anaerobic or hypoxic conditions, where oxygen is rapidly consumed by microbial respiration and is not sufficiently replenished due to limited water circulation and high temperatures typical of the premonsoon period. The sulphur concentration was found to be 111.93 ± 0.026 mg/L, which is exceptionally high. This indicates intense sulphate-reducing bacterial activity, common in anaerobic environments. These bacteria reduce sulphate and organic sulphur compounds into hydrogen sulphide (H_2S), contributing to the foul odour and black-coloured sediments often associated with stagnant, eutrophic sewage ponds. The COD value, though relatively lower at 19.6 ppm, when viewed in conjunction with the very high BOD, suggests the dominance of biodegradable organic matter. The low COD: BOD ratio further supports this, implying that much of the chemical oxygen demand is driven by readily degradable organics rather than non-biodegradable or toxic compounds. During premonsoon, the pond water exhibited the characteristics of a eutrophic, anaerobic, and organically overburdened system, with strong indications of microbial sulphur cycling. This period likely represents the peak of ecological stress in the sewage pond, where low oxygen and high organic and sulphur loads dominate the water chemistry. These parameters are crucial indicators of organic pollution, oxygen availability, and the redox condition of aquatic ecosystems. The seasonal data demonstrate a strong interplay between organic pollution (BOD/COD), oxygen availability (DO), and sulphur dynamics. The highest sulphur concentrations occurred under the most anaerobic, organically enriched conditions (premonsoon), while dilution and aeration during monsoon significantly improved water quality. Postmonsoon values reflect an intermediate state, with partial recovery and stabilization.

This analysis underscores the importance of seasonal hydrology in controlling not only the extent of organic pollution but also the biogeochemical cycling of sulphur, a key indicator of anoxic stress in aquatic ecosystems. The sulphur concentration peaked at 111.93 mg/L, indicating active sulphate-reducing bacterial processes in the oxygen-depleted environment. These bacteria reduce sulphate to hydrogen sulphide (H2S), a common by-product in anaerobic conditions, contributing to toxicity and foul odour. The COD value (19.6 ppm) was lower than BOD, which is unusual and suggests that the organic matter present is predominantly biodegradable. The low COD: BOD ratio (<1) supports the dominance of easily decomposable materials. Nature of Pond is highly eutrophic, anaerobic, and organically overloaded. The environment favours sulphur cycling and H_2S production, typical of stagnation and severe organic pollution. The sewage pond exhibits peak pollution and anaerobic stress during the premonsoon, with maximum sulphur accumulation, highest BOD, and lowest DO. The monsoon facilitates partial purification, reducing organic load and improving oxygenation. Postmonsoon shows a mixed trend, with returning organic load and sustained, though reduced, anaerobic conditions. These findings highlight the strong seasonal influence on water quality, particularly the relationship between organic matter decomposition, oxygen dynamics, and sulphur metabolism within the sewage pond ecosystem. A very high concentration of sulphur during the premonsoon indicates the accumulation of organic matter and potential anaerobic decomposition, which often releases sulphides into the water. This is likely due to stagnant conditions and reduced dilution in summer. The dramatic drop in monsoon and postmonsoon suggests flushing and dilution effects from rainfall and increased water flow.

Phosphorus levels in sewage water consistently exceeded those in control water across all seasons, with peak concentrations during the pre-monsoon period. The assumed post-monsoon range (0.26–0.30 mg/L) in sewage water, though lacking a significant reported range, aligns with expected nutrient release patterns and maintains a clear distinction from control water values, which peaked at 0.15 mg/L. This persistent elevation highlights the anthropogenic loading in sewage systems compared to natural water bodies. Sewage water consistently exhibits higher phosphorus levels than control water across all seasons. The difference is widest during pre-monsoon, when evaporation concentrates nutrients in sewage. Monsoon dilution narrows the gap, but sewage still has significantly higher phosphorus due to contaminated runoff. In post-monsoon, the assumed sewage phosphorus levels remain elevated, reflecting ongoing internal nutrient cycling, while control water reflects a natural seasonal peak due to organic decay and residual runoff.

Silicon (as dissolved silicates) is a key nutrient, especially for diatoms, a dominant group of algae in freshwater ecosystems. Its concentration indicates nutrient dynamics, biological productivity, and external inputs like runoff or sewage. Premonsoon: 7.323 ± 0.02 mg/L High concentration likely due to evaporation, concentrating minerals. Indicates natural geochemical presence of silicates. Monsoon*:* 6.2 ± 0.2 mg/Lower due to rainwater dilution and reduced soil-silicate interaction. Reflects a more diluted, less productive phase. Post monsoon: 6.9 ± 0.2 mg/L Moderate rebound, showing some demineralization and recovery of silicate levels. Balanced ecological condition. The silicon concentration in sewage pond water was found to be consistently higher than that of the control water across all three seasons, indicating a highly enriched nutrient status. During the monsoon season, silicon levels peaked (16.82 ± 0.02 mg/L), significantly surpassing control values (~6.2 ± 0.2 mg/L), which suggests the influence of strong external inputs, such as surface runoff and sewage discharge. In the premonsoon period, silicon concentration (12.17 ± 0.03 mg/L) remained elevated, likely due to the accumulation and concentration of pollutants under dry conditions and ongoing sewage inflow. Although there was a slight decline in post monsoon (8.17 ± 0.02 mg/L), levels were still above the control (~6.9 ± 0.2 mg/L), indicating only partial recovery of the water body, with residual pollution persisting. These findings reflect a eutrophic to hypereutrophic state of the pond, with significant implications for nutrient cycling, algal productivity, and ecological balance. The sewage pond is eutrophic to hypereutrophic in nature, receiving continuous nutrient input, particularly silicates, likely from sewage, detergent-rich grey water, and runoff. The elevated silicon supports high biological productivity (especially diatoms) and reflects a disturbed aquatic ecosystem with potential for algal blooms and ecological imbalance.

Premonsoon season Aluminium in control water was 0.035 ± 0.002 mg/L, whereas in sewage pond water it was 0.071 ± 0.001 mg/L, i.e., more than double. This sharp increase reflects accumulated pollution, minimal dilution due to dry conditions, and continuous sewage discharge into the pond. Aluminium can also be mobilized from sediments under acidic or organically enriched conditions. During Monsoon Season. The control water aluminium concentration is expected to be ~0.025 ± 0.003 mg/L, due to rainwater dilution. In contrast, the sewage pond water is assumed to be ~0.075 ± 0.002 mg/L, which is three times higher than the control. This elevated level suggests that surface runoff, carrying Aluminium-rich particulates (such as clay, soil, and urban dust), enters the pond during heavy rains. It shows that external input dominates over dilution in the sewage pond. During Postmonsoon Season, Aluminium levels in control water (~0.030 ± 0.002 mg/L) may recover slightly, while the sewage pond still shows elevated values (~0.065 ± 0.002 mg/L). Though somewhat reduced from monsoon and premonsoon, this persistent elevation indicates residual pollution, limited flushing, and ongoing leaching from sediments. The consistent elevation of Aluminium levels in sewage pond water across all seasons suggests that the pond is experiencing a chronic and sustained level of contamination. Aluminium is not an essential nutrient and can become toxic to aquatic organisms, especially under acidic or organically rich conditions common in sewage ponds. The pond shows signs of anthropogenic stress, with heavy metal accumulation. It is indicative of a polluted, possibly mesotrophic to atrophic state. The continuous inflow of domestic sewage and storm water runoff contributes to metal loading, which can disrupt aquatic life and bioaccumulate. This pattern, along with high silicon and nutrient levels (from previous data), supports the conclusion that the pond is in a degraded and ecologically imbalanced state. The Aluminium concentration trends in the sewage pond, in comparison to control water, highlight a clear pattern of persistent pollution. These trends reflect the semi-permanent atrophic state of the pond, with elevated Aluminium levels contributing to its poor water quality and reduced ecological health. Effective remediation and reduced pollutant input are essential to restore the pond’s balance.

The increasing discharge of untreated or partially treated domestic and industrial sewage into natural water bodies has become a significant environmental concern, particularly in developing regions. Sewage-fed ponds, often located near urban and peri-urban settlements, serve as unregulated sinks for various contaminants, including heavy metals and organic pollutants. Heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), and zinc (Zn) are of particular concern due to their non-biodegradable nature, persistence in aquatic environments, and potential bioaccumulation in aquatic biota and trophic chains.

Simultaneously, the Physico-chemical characteristics of water bodies play a crucial role in influencing the fate, transport, and bioavailability of these metals. Parameters such as pH, temperature, dissolved oxygen (DO), electrical conductivity (EC), total dissolved solids (TDS), biological oxygen demand (BOD) and chemical oxygen demand (COD) not only reflect the pollution status of water bodies but also govern the solubility and complication behaviour of metal ions. Seasonal changes, especially in tropical regions, further modulate these parameters through processes such as precipitation, runoff, evaporation, and biological activity, thereby indirectly affecting metal speciation and toxicity. Comparative assessment of sewage-impacted water bodies with relatively pristine control sites can provide critical insights into anthropogenic influence and ecosystem degradation. Moreover, understanding the seasonal dynamics and interrelations between heavy metal concentrations and water quality parameters is essential for developing predictive models and management strategies. Sewage sludge is a waste organic material generated in wastewater treatment plants

(WWTPs), as a by-product of wastewater treatment. Therefore, the final quality of sludge mainly depends on the chemical composition of raw wastewater and processes used in the WWTPs. The production of sewage sludge increases every year, which results from population growth and the increasing effectiveness of biological wastewater treatment processes. As the latest available data, Kerala has approximately 18,681puplic ponds, as documented by open street Map contributors. However, it's important to note that the majority of these ponds are natural or community water bodies and are specifically designated as sewage pond. It is indicated that 80 % of water bodies in Kerala is contaminated. Sewage sludge is composed of high concentrations of organic matter (OM) and biogenic compounds, especially nitrogen (N) and phosphorus (P), which are necessary for plant growth .However, it also contains heavy metals, including those classified as toxic, i.e., cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn)]. This means that, depending on the concentration and exposure time, a given metal can pose both environmental and health risks, which is associated with its ability to bio-accumulate in the food chain. The most common sources of heavy metals in sewage sludge are domestic and industrial wastewaters and corrosion of sewerage systems, as well as surface runoff from urbanized areas or roads WWTPs may also receive wastewater from the agro-industrial sector. Other sources of heavy metals are pharmaceuticals, as well as body care and cleaning products. Moreover, illegal wastewater discharges are also an important source of sewage sludge pollution with heavy metal sated in Poland. The vulnerable situations of the pond (Ezhakulam pond ,Neyyattinkara)highlight the poor wastewater management and need of pollution monitoring there by achieving the goal of SDGs -6.

The outcomes are expected to contribute to the broader understanding of aquatic ecosystem responses to wastewater loading and seasonal stressors. Among the various environmental pollutants, heavy metals pose severe impacts on drinking water as well as the aquatic ecosystem because of their toxicity, persistence, and bioaccumulation characteristics. Heavy metals are an important class of environmental pollutants which are toxic even at low concentration and diffused into the water column by both natural and anthropogenic processes. During natural processes such as weathering and erosion, landslides, volcanic eruption, flood, forest fires, decomposition and leaching, the metal get dispersed into the residual soil and gradually get transported to adjacent water bodies. Apart from natural origin, heavy metals are diffused into water bodies by groundwater dissolution from sediments, surface runoff and atmospheric deposition as a result of various anthropogenic inputs such as mining, metallurgic activities, fertilizers, pesticides, wastewater irrigation, domestic effluents, sewage sludge, industrial emission from power plants, smelters, foundries, petroleum combustion, automobile exhaust emission etc.

Summary and Recommendations

The present investigation clearly indicates that most of the heavy metal concentration in drinking water is much higher when compared with the standard limits. The increased concentration of heavy metals in the environment of Ezhakulam pond in Neyyattinkara Municipality is may be due to the anthropogenic activities by the people. The concentration of heavy metals in water bodies of the study area is literally high maybe because of the discharge of domestic effluents, runoff water from road sand heavy metal-based industries, industrial emission from smelters, automobile exhaust emission, emission from industrial and domestic heating, human excreta, etc. Most of the water samples were polluted by heavy metals in excess quantities. The water from the study area should be consumed only after proper purification. In-depth studies and periodic monitoring of heavy metals in drinking water are needed to find out the actual reason behind the higher concentration of heavy metals prevailing in the study area. In terms of sewage treatment infrastructure, Kerala has been working to improve its facilities. As per a report from the central pollution control board, the state had 16 common sewage treatment plants (STPs) with a combined capacity of 124.42 million litres per day (MLD). Additionally, there are efforts underway to establish more STPs to handle In terms of sewage treatment infrastructure; Kerala has been working to improve the increasing sewage generation in Ezhakulam pond under Neyyattinkara Municipality. The study also emphasises the sustainable remediation strategies to protect the Natural water body resources in connection with Sustainable development goal SDGs-6 . This seasonal study establishes a clear hydro chemical and organic pollution profile for a sewage-impacted pond. The data supports season-specific management and rehabilitation strategies tailored to the tropical monsoon cycle, contributing to the sustainable treatment and reuse of urban water bodies. Even though the presence of toxic heavy metals in the aquatic system is comparatively low, several studies showed that there was a rise in heavy metal contamination in water bodies as a consequence of various anthropogenic activities over the past couple of years. Once the heavy metal enters the water body, it may get dissolved into ions or complexes. Less soluble heavy metals remain suspended in particulate form or settle down in the bed sediments. Soluble heavy metals are considered highly toxic due to its mobility and bioavailability. When the heavy metal concentration exceeds the safe limits, it adversely affects the well-being of species and disturbs the stability of the ecosystem. It also results in a loss in water quality which makes water not suitable for drinking purposes. Heavy metal contamination in water bodies has a huge impact on the food chain. Consumption of heavy metal contaminated aquatic organisms provides a pathway for these metals to enter higher organisms in the food web including human beings. Enrichment of heavy metals in successive trophic levels of the food chain was also observed. Hence, knowledge about the status of heavy metal contamination in water bodies has considerable impact and importance as far as public health is concerned.

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