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Evaluation of Seasonal Variations in Water Quality and Microbial Contamination of the Kallada River, Kerala

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Abstract
The Kallada River, a major west-flowing river in Kerala, serves as a critical source of drinking water, irrigation, fisheries, and ecological support. Increasing anthropogenic pressures, including sand mining, agricultural runoff, sewage discharge, pilgrimage activities, and riparian degradation, have adversely impacted its water quality. This study evaluated the physicochemical and bacteriological characteristics of the Kallada River at eight sampling stations during pre-monsoon, monsoon, and post-monsoon seasons from November 2022 to July 2023. Water samples were analyzed for temperature, pH, total dissolved solids (TDS), electrical conductivity, alkalinity, hardness, free carbon dioxide, nitrate, phosphate, sulfate, sodium, potassium, and total coliform counts using standard analytical procedures. Results indicated seasonal variations in water quality parameters, with most physicochemical parameters remaining within permissible limits established by Indian standards. However, elevated phosphate concentrations and exceptionally high total coliform counts reflected significant anthropogenic contamination. Site 1 consistently exhibited greater deterioration in water quality, primarily due to intensive human activities associated with the Sabarimala pilgrimage. Pearson correlation analysis revealed significant relationships among physicochemical parameters across seasons, underscoring the influence of nutrient enrichment, runoff, organic matter decomposition, and mineralization processes. Although the river water generally meets criteria for Class C surface water, it is unsuitable for direct consumption without treatment and disinfection. Continuous monitoring and implementation of effective management strategies are necessary to safeguard the ecological integrity and water quality of the Kallada River.

Keywords: Kallada River; Water Quality Assessment; Seasonal Variation; Physicochemical Parameters; Microbial Contamination

Introduction
Rivers are important freshwater resources that support drinking water supply, irrigation, fisheries, transportation, energy production, and ecological sustainability. Rivers are an important part of Kerala's landscape, and the flowing water of the rivers is the State's most characteristic feature. Freshwater ecosystems occupy less than one percent of the Earth's surface but support 10% of all known species, highlighting their ecological significance (Dudgeon et al., 2006). It also plays an important role in nutrient cycling, sediment transport, groundwater recharge, and biodiversity conservation, and contributes to sustainable development (Vorosmarty et al., 2010). Yet almost all these rivers are either dead or are on the verge of death. Accelerating denudation of catchment area's vegetation cover, construction of large dams across the rivers, exploitive and indiscriminate sand mining from the river bed, pollution of river water, agricultural runoff, destruction of riparian vegetation, encroachment of river banks, and intrusion of salinity into the far inland areas of the rivers etc, have resulted in a shocking imbalance in the river basin of Kerala (Varghese, 2012; Bijukumar and Sushamma, 2000).

River pollution in India has reached a crisis point due to the need for freshwater to meet the needs of an increasing population, a growing economy, changing lifestyles, and evolving consumption patterns (Shrivastava et al., 2015). The ecosystem balance in a riverine system has always been in correspondence with the physico-chemical characteristics of water. Water quality is an important aspect, as poor quality will adversely affect the normal functioning of all systems. Hence, it is essential to verify the water quality before use. The extent of analysis of water for its quality is totally dependent upon the purpose for which the water is to be used. Regular monitoring of river quality provides valuable information on the eco-hydrologic conditions of a river basin.

Kallada River is one of the major west-flowing rivers in Kerala due to uncontrolled sand mining, Sabarimala pilgrimage, reclamation, poaching, etc. Considering the ecological and socio-economic importance of the river, the present study was undertaken to assess the physicochemical and bacteriological characteristics of the Kallada River during different seasons.

Materials and Methods
Description of the Study Area
The Kallada River is located on the western slopes of the Western Ghats in the Kollam and Thiruvananthapuram districts of Kerala, India. The Kallada River is formed by the three rivers, i.e., Kulathupuzha, Chendurni, and Kalthuruthy, which join near Parappar. The river originates in the Papanasam hills, south of Kulathupuzha in the Quilon district, at an altitude of 900 m above MSL. The river is 121 km long, and its drainage area is 1996 km². The Kallada river lies between 8° 49′N - 9° 17′N latitude and 77° 16′E - 76° 24′ E longitude. The basin is bounded by the Achenkovil basin in the North and the Ithikkara basin in the South. The Kallada reservoir is also a major source of irrigation and water supply to the agricultural fields in Kollam district. Most of the population depends on river water for irrigation and drinking through various projects. The Japan Bank for International Co-operation project covers 13 Grama Panchayats and 1 municipality, with a tapping point on the Kallada River at Tholicodu and a treatment plant with a capacity of 73 MLD, integrated into the distribution network. The Kallada River also has intake arrangements at Punalur town, with a treatment plant at Elampal with a capacity of 16 MLD. The river is a crucial water source for the population residing in the four taluks- Pathanapuram, Kottarakkara, Kunnathur, and Quilon- and it ends at Ashtamudi Lake.

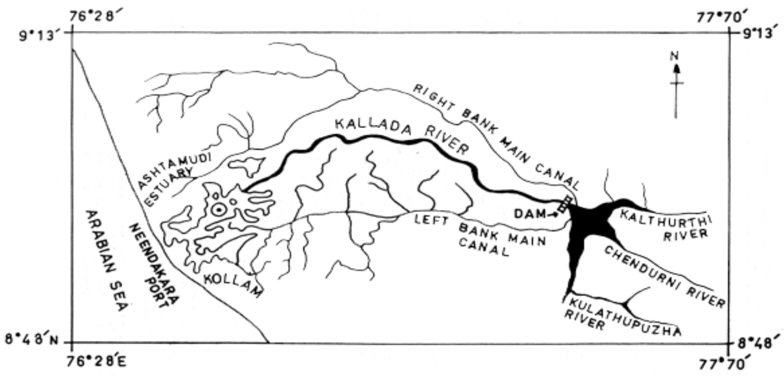


Fig. 1. Map of the Kallada River

Sampling Sites
The eight sampling sites were selected based on varying anthropogenic influence: Krishnankovil (Site 1), Maniyar (Site 2), Panampatta South (Site 3), Panampatta North (Site 4), Vettipuzha (Site 5), Pidavoor (Site 6), Fire Force (Site 7), and KSRTC Bridge (Site 8) of the river Kallada at Punalur town. The sites were selected based on different anthropogenic activities that have led to deterioration and influenced river water quality. Water samples were collected during three seasons - pre-monsoon, monsoon, and post-monsoon during the period of November 2022 to July 2023. Samples for analysis were collected directly from the river and stored in well-labeled, tightly capped, sterilized bottles. Separate sterile bottles were used for bacteriological analysis. The collected water samples were analyzed for various physical, chemical, and microbial parameters, including Temperature, pH, Total Dissolved Solids, Conductivity, Alkalinity, Nitrate, Nitrite, Sulphate, Phosphate, CO_2, Sodium, Potassium, and MPN, as per the standard methods of APHA (1998) and Trivedi and Goel (1986).

Results and Discussion
The results obtained from physico-chemical analysis of river water samples collected from the study area on a season-wise basis at eight sites, and the average values along with standard deviation are summarized in Tables 1 to 3.

Temperature is an important water quality parameter and is easy to measure in water bodies with low variation. The surface water temperature of the river ranged from 25 °C to 29 °C, as shown in Tables 1 to 3. The temperature showed a gradual increase till the onset of the monsoon season, a gradual decrease from the rainy season, and a slight increase in the post-monsoon months. The minimum temperature was observed during the monsoon at sites 1 to 5, but it increased from sites 6 to 8. The fluctuation in river water temperature depends on season, geographic area, sampling time, and river temperature (Ahipathy, 2006). pH is a measure of the concentration of hydrogen ions and is one of the most important parameters for assessing the acidic or basic character of water bodies. The pH of river water samples ranges from acidic to alkaline: 6.35 to 7.57, 5.85 to 7.74, and 6.07 to 7.58 in the pre-monsoon, monsoon, and post-monsoon seasons, respectively. The pH values of the samples during the sampling period were slightly acidic in all sites except at site 8. Except that some sites' pH values are well within the permissible range for drinking water, which is 6.5 to 8.5 as per IS: 2296.

The increase in organic pollution in this river must be one reason for the lowering of pH in certain areas, especially site I, in all seasons. According to Unnithan (2001), low pH could be due to exposure to relatively more acidic surface-basin soil, consequent on monsoon turbulence and bottom currents. A low pH can also result from the release of biogenic carbon dioxide from bacterial decomposition of organic matter (Berner, 1971). Benchamin et al., 2024, Shafer et al., 2021, and Chitra et al., (2022) also reported acidic pH values at different sites along the Kallada River. The total dissolved solids content is generally proportional to the degree of pollution. The TDS concentrations in the river water samples ranged from 0.020 to 0.080 mg/L, 0.020 to 0.059 mg/L, and 0.020 to 0.066 mg/L in the pre-monsoon, monsoon, and post-monsoon seasons, respectively, and were well within the limits set by the surface water quality standards as per IS:2296. Higher TDS values were observed in all seasons at sites 1 and 2; TDS values decreased abruptly from sites 3 to 7, followed by a gradual increase at site 8. The TDS concentration was high during the pre-monsoon season at site 2, possibly due to the addition of solids from surface runoff. Marker (1977) observed that the amount of total dissolved solids is influenced by plankton activity and organic materials. In a freshwater ecosystem, dissolved solids originate from natural sources and depend upon the location, geological basin of the water body, drainage, rainfall, bottom deposits, and inflowing water (Weber-Scannell and Duffy, 2007). Electrical conductivity measures a water sample's ability to conduct electric current and is directly related to the dissolved ions it contains. The higher the dissolved solids content, the greater the number of ions in water. Observed electrical conductivity values for the river water samples ranged from 0.034 mS/cm at site 1 (post-monsoon) to 0.037 mS/cm at site 4 (monsoon). The maximum value in the monsoon season indicates the presence of ions in the water. In the present study, all the conductivity values fell within the "no effect" range of 0-70 mS/cm for drinking water use. This indicates that no adverse effects associated with the water's electrical conductivity were expected.

Free carbon dioxide ranged from 10.38 to 46.40 mg/L, 9.0 to 41.0 mg/L, and 10.0 to 43.0 mg/L in pre-monsoon, monsoon, and post-monsoon river samples. A very high level of CO_2 is observed at all sites in all seasons, except at site 7 (monsoon). Surface water normally contains less than 10 mg free carbon dioxide per liter. (APHA, 1998). Free carbon dioxide in water accumulates due to microbial activity and organismal respiration. Hardness is the concentration of multivalent metallic cations in solution. The hardness concentration in river water samples during pre-monsoon, monsoon, and post-monsoon was found to be in the ranges of 13.33 to 45.33 mg/L, 15.33 to 55.3 mg/L, and 14.18 to 47.85 mg/L, respectively. Moreover, the hardness concentration at all sites did not pose any water quality problems, as it was within the recommended limit set by the surface water quality standard IS 2296. The results show a sudden increase in sites 1 and 2, a gradual decrease in sites 3 and 4, and a slight increase in site 5. Water with a total hardness of 0 to 60 mg/L is termed soft; 60 to 120 mg/L, moderately hard; 120 to 180 mg/L, hard; and above 180 mg/L, very hard. Based on this, the water samples in this study can be classified as soft water, as the total hardness limit is 13.33-55.3mg/L.

Total alkalinity is the capability of an aqueous solution to neutralize an acid. The mean alkalinity values in water samples ranged from 8.80 mg/L to 42.16 mg/L, 46.86 mg/L, and 40.52 mg/L during the pre-monsoon, monsoon, and post-monsoon seasons, respectively. The results show that the alkalinity values were high during the pre-monsoon, monsoon, and post-monsoon seasons at sites 1-3, and decreased gradually from sites 4-8; thereafter, there was little change. The alkalinity values at all sampling sites were within the WHO permissible limits.

The present study also revealed that the river's phosphate content ranged from 0.06 to 5.05 mg/L across different sites and seasons. The concentration of phosphate in the river shows significant seasonal variation. In both the pre-monsoon and monsoon seasons, the minimum phosphate value was observed at sites 1-3, and in the post-monsoon season, it was high at site 1. The high phosphate concentration at site 1 may be due to human and animal waste flushed into waterways, either from poorly treated sewage or from surface runoff. The BIS (Bureau of Indian Standards) suggested a limit of 0.1 mg/L for phosphate. The observed phosphate content of the river may be due to rainfall and land runoff, as reported by Persson and Jansson (1988) and White and Hammond (2009). Sulfate is widely distributed in nature and may be present in natural waters. The main sources of sulfur are rocks near water bodies and the biochemical activity of anaerobic bacteria. Sulfate concentrations in the water samples ranged from 3.33 mg/L to 19.98 mg/L, 3.56 mg/L to 19.30 mg/L, and 3.41 mg/L to 17.89 mg/L during the pre-monsoon, monsoon, and post-monsoon seasons, respectively, and were within the standard limit of 400 mg/L as per IS:2296. The comparatively low sulfate values on site 1 in all seasons. The lower sulfate values recorded could be due to sulfate easily precipitating and settling to the riverbed sediment.

Nitrate is an essential nutrient, but also a good indicator of contamination from natural and human activities. In the present study, nitrate ranged from 2.74 mg/L to 9.69 mg/L, which is within the 20 mg/L limit as per IS: 2296. The higher value was recorded from sites 1 and 5 in the pre-monsoon season. Nitrate levels in river water often show marked seasonal fluctuations, with lower concentrations observed at site 6 during the pre-monsoon to post-monsoon period. The comparatively high values at sites 1 and 5 could be attributed to anthropogenic sources, viz., runoff water, washing activities, and the discharge of effluents from retting activities containing nitrogen species, which are subsequently oxidized by microbiological activity under aerobic conditions. It is also reported that excessive nitrate in water is due to domestic activities and agricultural fertilizers (Camargo and Alonso 2006). Sodium ranks sixth in elemental abundance and is present in most natural waters. Surface water samples show higher sodium levels in the dry season than in the wet season. Sodium concentration ranged from 9 mg/L to 21.82 mg/L, and no sample from the study area exceeded the desirable permissible limit of 200 mg/L set by WHO in 2004. Potassium concentration ranged from 1.11 to 5.11 mg/L, and all samples were within the limit.

Coliform bacteria are used as indicators of water quality (Ashbolt et al., 2001). The results of the microbiological analysis showed that the total coliform count ranged from 956 to 1002 MPN/100 mL. The high pollution levels at all sites are due to anthropogenic disturbances. The monsoon season showed the lowest bacterial density due to dilution, and it is less polluted as it is the period before the pilgrimage season. During the post-monsoon season, the water is much more polluted, as it is the peak pilgrimage season.

The study found that the Kallada River water is more heavily contaminated during the Sabarimala pilgrimage season than during the off-season, due to pilgrims using it for various sanitary purposes. It was found that water quality deteriorated more at site 1 across all seasons studied. This is due to high levels of anthropogenic disturbance associated with the Sabarimala pilgrimage. Total coliform counts were very high across all sites and seasons. It is generally believed that the higher the MPN of coliforms, the higher the extent of pollution in a given sample, indicating heavy bacterial load and contamination. (Bhadra et al., 2003) The values, compared with Indian standards, confirmed that the water quality can be designated as class C; i.e., although fit for outdoor bathing, it is not fit for drinking purposes and requires conventional treatment followed by disinfection. Overall, the counts of various microbiological parameters indicate that the water of the Kallada River is polluted, in accordance with the standards of the Bureau of Indian Standards and the European Union.

Statistical Analysis

Correlation analysis of the Kallada River during the pre-monsoon, monsoon, and post-monsoon seasons elucidates the interactions among physicochemical parameters and their seasonal variability, as presented in Tables 4-6. In the pre-monsoon period, Pearson correlation analysis identified several significant relationships among these parameters, reflecting the effects of evaporation, reduced water flow, and increased concentrations of dissolved substances. A strong positive correlation was found between total dissolved solids (TDS) and pH ($r = 0.781$, $p < 0.05$), indicating that elevated dissolved mineral content contributes to the development of alkaline conditions in river water. Dissolved salts and ionic constituents are recognized as key factors influencing alkalinity and pH in freshwater ecosystems (Wetzel, 2001). TDS also exhibited a strong positive correlation with phosphate ($r = 0.733$, $p < 0.05$), suggesting nutrient enrichment associated with dissolved solids, likely resulting from agricultural runoff and domestic wastewater discharge, as reported in previous river water quality studies (Singh et al., 2004). Sodium and potassium demonstrated a very strong positive correlation ($r = 0.981$, $p < 0.01$), implying a shared origin from weathering processes or anthropogenic activities such as fertilizer application and sewage input (Hem, 1985). Electrical conductivity displayed moderate positive correlations with alkalinity and total hardness, indicating that dissolved ionic substances contribute to river mineralization (Boyd, 2000).

During the pre-monsoon season, significant negative correlations were observed among several water quality parameters. Alkalinity demonstrated a very strong negative correlation with phosphate ($r = -0.916$, $p < 0.01$), indicating that elevated phosphate concentrations reduced the river water's buffering capacity. Comparable nutrient interactions have been documented in freshwater systems experiencing eutrophication (Chapman, 1996). Electrical conductivity exhibited a strong negative correlation with total coliform count ($r = -0.939$, $p < 0.01$), suggesting that highly mineralized water conditions may inhibit microbial survival. The overall correlation pattern during the pre-monsoon period reflects concentration effects resulting from reduced river discharge and elevated evaporation rates, which are characteristic of tropical river systems (Trivedy and Goel, 1986). Nutrient enrichment, ionic accumulation, and anthropogenic influences, including agricultural runoff and sewage discharge, significantly impacted the river's water quality during this season (Manahan, 2017).

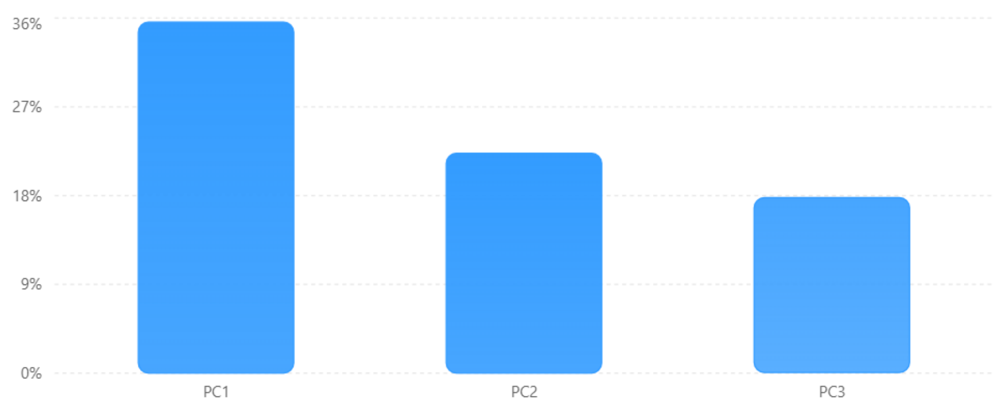
In contrast, the monsoon season exhibited distinct variations in correlation patterns due to heavy rainfall, increased surface runoff, and dilution effects. A strong positive correlation was identified between total dissolved solids (TDS) and total hardness ($r = 0.783$, $p < 0.05$), indicating that dissolved solids contributed substantially to hardness by transporting calcium and magnesium salts during runoff (Hem, 1985). TDS also showed a strong positive correlation with alkalinity ($r = 0.796$, $p < 0.05$), suggesting that bicarbonate and carbonate ions contributed simultaneously to both dissolved solids and alkalinity (Wetzel, 2001). pH exhibited a very strong positive correlation with phosphate ($r = 0.911$, $p < 0.01$) and total coliform ($r = 0.912$, $p < 0.01$), indicating enhanced nutrient availability and microbial growth under slightly alkaline conditions. Similar observations were reported by Vega et al. (1998) in studies of seasonal variations in river water quality. Electrical conductivity showed a strong positive correlation with free CO_2 ($r = 0.807$, $p < 0.05$), while nitrate was positively correlated with CO_2 ($r = 0.738$, $p < 0.05$), reflecting increased decomposition and microbial activity during the rainy season (Boyd, 2000).

Several significant negative correlations were identified during the monsoon season. Alkalinity demonstrated a strong negative correlation with phosphate ($r = -0.794$, $p < 0.05$), indicating a nutrient-induced reduction in buffering capacity, a phenomenon frequently observed in eutrophic freshwater environments (Chapman, 1996). Potassium exhibited significant negative correlations with both temperature ($r = -0.730$, $p < 0.05$) and pH ($r = -0.804$, $p < 0.05$), which suggests dilution or biological uptake during periods of increased runoff. A strong negative correlation was also observed between phosphate and potassium ($r = -0.843$, $p < 0.01$), reflecting distinct sources or utilization mechanisms. Electrical conductivity showed a significant negative correlation with sodium ($r = -0.760$, $p < 0.05$), primarily attributed to dilution effects from monsoon rainfall (Shrestha & Kazama, 2007). The monsoon season was thus characterized by increased nutrient transport, heightened microbial activity, and runoff-driven alterations in river water chemistry (Manahan, 2017). In the post-monsoon season, the river gradually stabilized after the intense rainfall, and correlation analysis revealed the ongoing influence of residual nutrients and decomposition processes. A strong positive correlation was found between total dissolved solids (TDS) and alkalinity ($r = 0.738$, $p < 0.05$), indicating that dissolved bicarbonates and mineral ions contributed substantially to river alkalinity (Wetzel, 2001). pH exhibited a strong positive correlation with phosphate ($r = 0.852$, $p < 0.01$), suggesting that phosphate availability increased under alkaline conditions, which is common in nutrient-rich aquatic ecosystems (Boyd, 2000). Electrical conductivity was strongly positively correlated with free CO_2 ($r = 0.775$, $p < 0.05$), indicating enhanced organic matter decomposition and accumulation of dissolved ions following the monsoon season (Trivedi and Goel, 1986). Moderate positive correlations among nitrate, electrical conductivity, and total hardness further underscored the influence of dissolved nutrients and mineral content in the river water (Hem, 1985).

Several significant negative correlations were found during the post-monsoon season. Alkalinity showed a very strong negative correlation with phosphate ($r = -0.897$, $p < 0.01$), indicating that higher phosphate levels reduced the water's buffering capacity. This matches what has been seen in eutrophic freshwater systems (Chapman, 1996). Total dissolved solids were strongly and negatively correlated with the total coliform count ($r = -0.810$, $p < 0.05$), indicating that higher mineral content was associated with fewer microbes. Free CO_2 also had a significant negative correlation with sodium ($r = -0.734$, $p < 0.05$), showing an inverse relationship between dissolved gases and ions. Overall, the post-monsoon season exhibited transitional water quality, with physicochemical parameters stabilizing, organic matter breaking down, and monsoon-derived nutrients still affecting the system (Singh et al., 2004).

Principal Component Analysis

Principal Component Analysis was used to identify the major factors that control the variation of water quality of the Kallada River. The first three principal components explained 75.7% of the total variance in the dataset as shown in Fig.2 and Table 7.The first principal component (PC1) explained 35.6% of the variance and had strong positive loadings for TDS, EC, alkalinity, and hardness, indicating the effects of mineral dissolution, ionic enrichment,and anthropogenic runoff.



Graph 1. Graph shows PCA Loading Plot Illustrating the Contribution of Water Quality Parameters to Principal Components in the Kallada River

The second principal component (PC2) accounted for 22.3% of the variance, with high positive loadings for sodiu m, potassium, nitrate,and hardness, indicating inputs from agricultural runoff and domestic waste. The third principal component (PC3) explained 17.8% of the variance and exhibited positive associations with phosphate and carbon dioxide, indicating the influence of organic matter decomposition and nutrient enrichment. The PCA results demonstrated that nutrient enrichment, sewage discharge, weathering processes, and seasonal hydrological changes are the major controlling factors influencing water quality in the Kallada River. The third (PC3) explained 17.8% of the variance and was positively associated with phosphate and carbon dioxide, reflecting the influence of organic matter decomposition and nutrient enrichment. The PCA results suggested that the major controlling factors affecting water quality in Kallada River are nutrient enrichment, sewage discharge, weathering processes and seasonal hydrological changes.

Table 1. Physico-chemical and bacteriological characteristics of water samples of Kallada River (Pre-monsoon)

Parameters	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Mean± SD
Temp (0°C)	26.5	27.0	27.0	27.8	27.6	27.2	26.7	27.5	28.08 ± 0.60
pH	6.42	6.59	6.77	6.35	6.57	6.86	6.64	7.57	6.72 ± 0.38
TDS (mg/l)	0.04	0.06	0.03	0.02	0.02	0.02	0.02	0.03	0.03 ± 0.01
EC	0.07	0.11	0.04	0.10	0.04	0.03	0.03	0.05	0.05 ± 0.03
TH (mg/l)	37.68	47.85	17.65	25.49	45.38	22.44	14.18	32.00	26.5 ± 11.74
Alkalinity (mg/L)	40.52	35.11	34.20	11.61	13.09	8.71	10.16	8.71	19.5 ± 15.01
PO_4^{3-} (mg/L)	9.93	11.56	9.66	25.49	34.01	35.52	38.00	53.00	28.7 ± 16.26
SO_4^{2}- (mg/L)	3.41	3.96	15.05	5.41	17.65	7.89	17.78	2.52	9.1 ± 6.26
NO^{3}- (mg/L)	7.60	7.74	6.92	7.86	7.65	2.92	6.63	6.46	7.27 ± 2.05
CO_2 (mg/L)	24.58	23.71	18.91	43.66	21.82	13.34	10.55	24.62	22.93 ± 11.4
Na (mg/L)	20.40	20.72	20.38	20.29	23.56	20.37	20.30	20.27	20.78 ± 1.12
K (mg/L)	1.49	1.78	2.01	1.61	5.11	2.10	1.63	1.60	2.16 ± 1.20
TC (MPN/100ml)	991	956	986	987	992	985	983	989	985.7 ± 11.47

Table 2. Physico-chemical and bacteriological characteristics of water samples of Kallada River (monsoon)

Parameters	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Mean ± SD
Temp (0° C)	25.5	26.0	26.0	27.7	25.0	27.3	27.0	27.6	26.51 ± 1.01
pH	5.85	6.21	6.36	6.33	6.75	6.86	6.67	7.74	6.59 ± 0.56
TDS (mg/L)	0.059	0.053	0.030	0.030	0.025	0.026	0.020	0.030	0.03 ± 0.014
EC (mS/cm)	0.110	0.085	0.040	0.170	0.062	0.036	0.034	0.061	0.07 ± 0.04
Total Hardness (mg/L)	48.66	55.33	19.00	24.00	42.72	24.00	15.33	35.33	33.0 ± 14.70
Alkalinity (mg/L)	46.86	28.77	33.69	14.66	17.66	8.80	11.73	8.80	21.3 ± 13.75
PO_4^{3-} (mg/L)	12.00	11.66	7.80	17.40	30.40	37.03	38.12	54.04	26.0 ± 16.39
$SO_4^{\ 2-}$ (mg/L)	3.56	4.58	16.08	6.60	18.03	5.96	19.30	1.35	9.43 ± 7.16
NO^{3-} (mg/L)	5.90	8.38	7.00	8.64	5.75	2.74	5.20	6.79	6.3 ± 1.88
CO_2 (mg/L)	20.00	28.71	19.14	41.80	17.42	16.57	9.00	29.83	22.8 ± 10.17
Na (mg/L)	21.49	20.74	20.38	11.93	20.58	20.40	20.36	20.67	19.5 ± 3.10
K (mg/L)	3.45	3.29	2.98	3.06	3.51	2.09	1.66	1.11	2.6 ± 0.90
Total Count (MPN/100ml)	977	984	988	988	988	993	983	1002	990.5 ± 7.27

Table 3. Physico-chemical and bacteriological characteristics of water samples of Kallada River (post-monsoon)

Parameters	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Mean ± SD
Temp(0°c)	26.5	27.0	27.0	27.8	27.6	27.2	26.7	27.5	27.16± 0.45
pH	6.07	6.31	6.50	6.28	6.59	6.79	6.65	6.65	6.59 ± 0.46
TDS (mg/L)	0.047	0.066	0.030	0.027	0.024	0.024	0.022	0.032	0.03 ± 0.01
EC (µS/cm)	0.072	0.108	0.043	0.104	0.049	0.035	0.034	0.052	0.06 ± 0.02
Total Hardness (mg/L)	37.68	47.85	17.65	25.49	43.58	22.44	14.18	32.00	30.1± 12.22
Alkalinity (mg/L)	40.52	35.11	34.20	11.61	13.09	8.71	10.16	8.71	20.2 ±13.73
PO_4^{3-} (mg/L)	9.93	11.56	9.66	25.49	34.01	35.52	38.00	53.00	27.1± 15.81
SO_4^{2-} (mg/L)	3.41	3.96	15.05	5.41	17.65	7.89	17.78	2.52	9.20 ± 6.55
NO^{3-} (mg/L)	7.60	7.74	6.92	7.86	7.65	2.92	6.63	6.46	6.72 ± 1.62
CO_2 (mg/L)	24.58	23.71	18.91	43.66	21.82	13.34	10.55	24.62	22.64 ± 9.9
Na (mg/L)	20.74	20.52	20.18	15.92	21.82	20.18	20.13	20.27	19.97± 1.72
K (mg/L)	2.45	2.51	2.47	2.31	4.24	2.07	1.63	1.31	2.37 ± 0.86
Total Count (MPN/100ml)	974	960	977	978	980	979	973	983	975. ± 7.03

Table 4. Physico-chemical and bacteriological characteristics of water samples of Kallada River (post monsoon)

	Temp	pH	TDS	EC	TH	Alk	Phos	Sulphate	Nitrate	CO_2	Na	K	TC
Temp (0°c)	1												
pH	-.102	1											
TDS (mg/l)	-.351	.781*	1										
EC	.373	.020	-.009	1									
TH (mg/l)	.259	-.003	-.036	.516	1								
Alk (mg/l)	.566	-.274	-.454	.608	-.008	1							
Phos (mg/l)	-.506	.572	.733*	-.365	.148	.916**	1						
Sulphate (mg/l)	-.297	-.108	.022	-.427	.088	-.316	.187	1					
Nitrate (mg/l)	-.003	-.461	-.119	-.049	.203	.224	-.244	.172	1				
CO_2 (mg/l)	.421	-.473	-.286	27	.223	-.045	-.078	-.384	.418	1			
Na (mg/l)	-.016	-.195	-.189	-.076	.704	-.195	.156	.510	.480	.109	1		
K (mg/l)	-.014	-.136	-.185	-.175	0.631	-.274	.210	.604	.349	.038	.981**	1	
TC (MPN/100ml)	-.196	.123	.077	-939**	-.341	-.547	.386	.296	.146	.245	.181	.259	1

*. Correlation is significant at the 0.05 level (2-tailed). Correlation is significant at the 0.01 level (2-tailed).

Table 5. Pearson Correlation Coefficient of Kallada River (pre-monsoon season)

	Temp	pH	TDS	EC	TH	Alk	Phos	Sulphate	Nitrate	CO_2	Na	K	TC
Temp (0°c)	1												
pH	-.102	1											
TDS (mg/l)	-.351	.781*	1										
EC	.373	.020	-.009	1									
TH (mg/l)	.259	-.003	-.036	.516	1								
Alk (mg/l)	.566	-.274	-.454	.608	-.008	1							
Phos (mg/l)	-.506	.572	.733*	-.365	.148	.916**	1						
Sulphate (mg/l)	-.297	-.108	.022	-.427	.088	-.316	.187	1					
Nitrate (mg/l)	-.003	-.461	-.119	-.049	.203	.224	-.244	.172	1				
CO_2 (mg/l)	.421	-.473	-.286	-.127	.223	-.045	-.08	-.384	.418	1			
Na (mg/l)	-.016	-.195	-.189	-.076	.704	-.195	.156	.510	.480	.109	1		
K (mg/l)	-.14	-.136	-.185	-.175	0.631	-.274	.210	.604	.349	.038	.981**	1	
TC (MPN/100ml)	-.196	.123	.077	-939**	-.341	-.547	.386	.296	.146	.245	.181	.259	1

*. Correlation is significant at the 0.05 level (2-tailed). Correlation is significant at the 0.01 level (2-tailed).

Table 6. Pearson Correlation Coefficient of Kallada River (monsoon season)

Parameter	Temp	pH	TDS	EC	TH	Alk	Phos	Sulphate	Nitrate	CO2	Na	K	TC
Temp (0°c)	1												
pH	.498	1											
TDS (mg/l)	-.416	-.596	1										
EC	.132	-.425	.413	1									
TH (mg/l)	-.559	-.243	.783*	.276	1								
Alk (mg/l)	-.677	-.771*	.796*	.225	.474	1							
Phos (mg/l)	.505	.911**	-.575	-.410	-245	.794*	1						
Sulphate (mg/l)	-.353	-.094	-.583	-.439	-.470	-.096	-.064	1					
Nitrate (mg/l)	-.016	-.246	.347	.634	.292	.272	-.455	-.179	1				
CO_2 (mg/l)	.391	.004	.245	.807*	.222	-.058	-.175	-.604	.738*	1			
Na (mg/l)	-.0.51	.134	.218	-.760*	.327	.278	.172	.095	-.475	-.724*	1		
K(mg/l)	-.730*	-.804*	.518	.457	.492	.680	-.843**	.116	.340	.152	-.135	1	
TC (MPN/100ml)	.566	.912**	-.519	-.254	-.244	-.703	.705	-.259	-.096	.272	-.063	-.657	1

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Table 7. Principal Component Analysis (PCA) Showing Variance Explained and Dominant Water Quality Parameters

Principal Component	Variance	Dominant Parameters
PC1	35.6	TDS, EC, Alkalinity, Hardness
PC 2	22.3	Na, K, NO_3, Total hardness
PC 3	17.8	PO_4, CO_2

Conclusion

This study assessed seasonal variations in the physicochemical and bacteriological characteristics of the Kallada River at eight sampling stations in Punalur, Kerala. Most physicochemical parameters remained within permissible limits for surface water; however, localized anthropogenic activities significantly impacted overall water quality. Parameters including temperature, pH, total dissolved solids, electrical conductivity, total hardness, alkalinity, sulphate, sodium, and potassium consistently met acceptable standards. In contrast, elevated concentrations of free carbon dioxide, phosphate, nitrate, and especially total coliform bacteria at specific locations indicated organic pollution and microbial contamination resulting from domestic wastewater discharge, surface runoff, pilgrimage activities, and other human interventions. Krishnankovil (Site 1) consistently exhibited poorer water quality than other stations, reflecting the cumulative effects of intense anthropogenic pressure. Seasonal patterns were observed: the pre-monsoon season showed higher concentrations of dissolved constituents due to reduced river flow and increased evaporation, while the monsoon and post-monsoon seasons were marked by greater nutrient loading, sediment transport, and microbial contamination from rainfall-induced runoff. Pearson correlation analysis revealed significant relationships among several physicochemical parameters, suggesting that river water chemistry is influenced by natural geochemical processes, nutrient cycling, organic matter decomposition, and human activities. Although the Kallada River remains a vital freshwater resource for drinking, irrigation, fisheries, and ecological sustainability, persistently high total coliform counts indicate that the water is unsuitable for direct consumption without adequate treatment and disinfection. This study provides essential baseline data for future water quality monitoring, pollution control, and sustainable river management, supporting the long-term conservation and ecological health of the Kallada River ecosystem.

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Author Contributions

RA conceptualized the study, AUR conducted the field investigations, collected data, and performed laboratory analysis. AG conducted statistical analysis, drafted the original manuscript, and supervised the research. JRF revised and edited the manuscript. RV edited and finalized the manuscript for the final publication.

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